# RECONNAISSANCE FOR SECONDARY RECOVERY, THROUGH RESERVOIR CHARACTERIZATION AND ANALYSIS OF THE LOWER SILURIAN CLINTON SANDSTONE, THE APPALACHIAN BASIN

A Thesis submitted for partial fulfillment of requirements for the degree Bachelor of Science in the Department of Geological Sciences of The Ohio State University

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The work presented in this thesis is incomplete. The purpose was to aide in the planning and developing of a Secondary Recovery Project. A significant amount of data collection and analysis remains to be completed, before any serious investment can be deemed appropriate. I believe with supreme confidence that currently an industry is developing, that will provide the incentive for private investment to complete what is only hinted to here. Management of our resources and their byproducts, specifically carbon dioxide from the burning of fossil fuels, will prove to be a crucial factor in the future success of our civilization.

I would like to thank Dr. Krissek most importantly for his patience and assistance in confining my ideas into a fairly coherent thesis. His influence greatly improved the quality of this work.

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**Abstract** The lower Silurian Clinton sandstone has been a prolific producer of hydrocarbons since the end of the 19$^{th}$ century. Reservoir conditions are typically poor with low permeability and porosity; so low that in most cases the Clinton is classified as a tight gas formation. The gas-to-oil ratio of this producing formation is very high, with production records proving it to be overall a much more prolific producer of gas than oil. The majority of oil produced from this interval comes from the central part of Ohio, as the formation pinches out a small distance farther west. The majority of gas comes from the easternmost part of the state, deeper within the Appalachian Basin. In Ohio more than 70,000 Clinton wells have been drilled to date. The major pools have been discovered, primary production has dwindled with depletion of reservoir pressure. Numerous small-scale tectonic structures that have a significant influence on hydrocarbon accumulation may have been missed, during development of this horizon. Locations where significant hydrocarbons have been produced and primary production has been exhausted provide feasible opportunities for secondary recovery methods. Understanding the complex geology and reservoir parameters of this petroleum system will be instrumental in the success of any secondary recovery attempts.

## Introduction

This paper considers the Clinton Formation of Ohio, which is different than the Clinton Group of the eastern Appalachian Basin. Even though the two units share similar structural characteristics, they were deposited at different geologic times. The Clinton Sandstone of Ohio was deposited during the Alexandrian Epoch, whereas the Clinton Group to the east was deposited almost completely during the Niagaran Epoch.

The Clinton Sandstone of Ohio is a stratigraphically informal designation adopted by drillers. The interval of interest consists of the Lower Silurian from the easternmost part of Ohio to the central part of the state, where this part of the section pinches out. The formal stratigraphic units of interest include the lowermost part of the Silurian section, the Brassfield Formation, and extend up to the contact with the Big Lime (also a drillers term) whose lowest unit is the Lockport Dolomite. For the remainder of this paper this section will be called the Clinton Interval, and emphasis will be placed on its sandstone portions because they contain the most significant hydrocarbon reserves.

## Geologic History

The geologic history recorded by the Clinton Interval began roughly 440 million years ago. The Clinton Interval, characterized by an intricate system of marine to non-marine settings was deposited in a foreland basin during the large scale erosion of the Taconic Mountains, which were formed during middle to late Ordovician time as a result of plate tectonic interactions. The area of interest in this paper was located just south of the equator during its formation.

The Laurentia landmass, on which the present day Appalachian Basin of North America resided, was involved in a collision with a group of volcanic arc islands, which were part of the Avalonia plate. The more dense oceanic crust of the Avalonia plate was subducted under the less dense continental crust of Laurentia plate. This collision proceeded until late Ordovician time when the interaction between the two plates decreased. Igneous rocks to the east of the zone occupied by the foreland basin, dated using radiometric methods, indicate that the Taconic Orogeny ended near the close of the

Ordovician Period. The best present-day case of this type of subduction-related mountain- building event is in South America, where the Andes Mountains have been produced.

The majority of Cambro-Ordovician stratigraphic units in eastern Laurentia are carbonate rocks that were deposited on a shallow platform, with some shale representing an occasional influx of siliciclastic sediment (Drozd and Cole, 1994). The Trenton Limestone of middle to late Ordovician age was deposited in a subtidal environment, ranging from open shelf to platform settings. Southeast of this carbonate buildup, organic rich black shale was deposited (Drozd and Cole, 1994). This large section of black shale has been given different names in different areas, including Antes Shale, Utica Shale, and Reedsville Shale, among others, and has been broken into more units than simply the Point Pleasant Formation. For the remainder of this paper the entire section of middle to upper Ordovician black shales, excluding the Queenston Formation, will be called the Point Pleasant Formation (Figure 1).

Sediment was being supplied from the eastern area of uplift at a faster rate than the subsidence of the foreland basin; this provided a large influx of siliciclastic sediment that terminated the deposition of the Trenton Limestone and the Point Pleasant Formation as the shoreline of the Utica Sea was forced westward. Precambrian zones of weakness greatly affected patterns of early Paleozoic sedimentation, diagenesis, and the potential for hydrocarbon accumulation, leading in part to the formation of the restricted interplatform basin in which the Point Pleasant Formation was deposited (Wickstrom, 1990).

During the late Ordovician, deep water depositional environments in the foreland basin, with abundant shales and turbidites, migrated west and gave way to nonmarine and shallow marine environments, including river systems, barrier islands, alluvial fans, and lagoons. The Clinton Interval lies unconformably on the older Ordovician units. Between late Ordovician time and the deposition of the Clinton Interval, nearly all of North America was above sea level, during which considerable erosion of the Ordovician units produced the post-Ordovician erosional surface. A complex of depositional settings, similar to those of the late Ordovician, returned after this period of erosion to create the setting for deposition of the Clinton Interval.

A major transgression eastward occurred after the long hiatus, producing the lower tongue of the Cabot Head Shale. During a subsequent regression the Clinton Sandstone was deposited in a deltaic setting. The Clinton Sandstone consists of three different types of bodies, any of which may or may not be present at a location. In stratigraphic order from deepest to shallowest, these three are the White, Red, and Stray Clinton Sandstone Bodies. Interbedded shales separated and intertongue with the sand bodies. The Taconic Highlands to the east provided the influx of siliciclastic sediment from which the Clinton sandstone is derived, producing viable reservoir rock. Knight (1969) suggests that minor amounts of the detritus in the Clinton Interval were carried into the area from the Laurentian Shield by longshore currents.

The Clinton Interval sandstone bodies are mostly sheetlike in eastern Ohio and more lenticular in central Ohio (Coogan 1991). This difference is a characteristic of proximity of the source area of sediment being derived from the Taconic Orogeny to the east, suggested by Drozd & Cole (1994). The depositional environment was incredibly complicated, and regional variability was significant as a result of the paleotopography and the distribution of delta systems and river/tidal channels. Knight (1969) concluded that the western shoreline of the Utica Sea was controlled by the ancestral Waverly and or Cincinnati Arches of central and western Ohio, respectively. The shoreline bordered a broad, mainly featureless plain that may have contributed a small amount of sediment to the sea. As the basin filled with sediment and sea level rose, the western shoreline transgressed westward while the eastern shoreline regressed westward, until the western shoreline reached into current day Illinois. This was followed by another major transgression, during which the upper tongue of the Cabot Head Shale was deposited. During further transgression, the entire unit was capped with the largely carbonate Packer Shell Unit.

## Tectonic Influences

Three major tectonic events affected rocks of the Appalachian Basin: 1) The Middle Proterozoic Grenville Orogeny that formed the basement; 2) The Early and Middle Cambrian episode of Eastern Interior Rifting that formed a graben in what was to become the center of the basin; and 3) The Appalachian Orogenies, including the Ordovician Taconic, Devonian Acadian, and the Pennsylvanian Alleghany, which created the foreland basin and deformed Paleozoic cover rocks.

Initially, (Root, 1958, et al earlier) it was believed that tectonics played a minor role, if any in the formation of the Clinton Interval. At the time little was understood about the basement fault-related features that are now realized to play an important, and in some areas pivotal role in the accumulation of hydrocarbons. In central and western Ohio, basement faults have been defined in a few localities, but the general lack of drilling and seismic exploration has hindered a better understanding of the structure in this area (Root and Onasch, 1999).

Four major fault systems affect the Clinton Interval (Figure 2): the Rome Trough, the Cambridge-Burning Springs, Star, and the Highlandtown. The COCORP seismic profile across Central Ohio provides the large-scale subsurface data needed to understand the major tectonic influences on the Clinton Interval. The Highlandtown and Star systems are localized features and will not be discussed in detail.

The Cambridge-Burning Springs fault system has been referred to as a monocline by Baranoski (1993) and as an arch by numerous other publications. The system has two parts: the Burning Springs portion lies in West Virginia, trending nearly north-south, and has only minimal effect in the southernmost part of Washington County, Ohio. The Cambridge segment begins just north of the Ohio River in Washington County and trends northwest, terminating just south of Lake Erie in Lorain County, Ohio (Root and Onasch, 1999). Others have suggested, however that the Cambridge fault zone terminates in Wayne County. The Cambridge-Burning Springs fault system is characterized by a zone of reactivated Paleozoic faults, several kilometers wide, embedded in the Precambrian Grenville basement (Root and Onasch, 1999). These faults are suggested by Root and Onasch (1999) to have originated from an older Precambrian basement structure. The degree and type of development of structures within the fault zone are not identical along its length, as displacement diminishes to the north; however structural elements and processes are common and comparable (Root and Onasch, 1999).

The Cambridge portion of this system is suggested by Root (1996) to be a narrow horst block about 1.5 km wide, bounded by normal faults dipping >80°. Within the

Clinton Interval, maximum displacement across the Cambridge fault is 18m. Variations in displacement upward in the section can be accounted for by either tectonic or sedimentological processes, as suggested by Root (1996). Interpretation of the COCORP seismic line by Dexling (1994) shows that the Cambridge fault system extends up into Devonian rocks. In these younger units the fault zone branches off into a flower-like structure. This flower structure, inferred by Root (1996), is a result of wrenching caused by deformation during the Alleghenian orogeny. To the west of the Cambridge fault zone lies a related synclinal structure, the Parkersburg-Loraine syncline. This related structure is inferred by the author to have structural significance in the region of study included in this thesis.

In northeastern Ohio the Highlandtown fault system consist of five fairly parallel faults, trending northwest, the Middleburg, Akron, Suffield, Smith Township, and Highlandtown faults (Figure 2). This complex fault system must have a significant influence on the Clinton Interval in this region, which has historically proven to be a prolific producer of hydrocarbons. The Starr fault system is a series of east-west trending faults located in southeastern Ohio. Brannock (1993) infers this system to be a series of high angle faults originating in the Precambrian strata,.

Root (1996) states that with our present knowledge, the Burning Springs-Cambridge fault zone and the Highlandtown fault zone dominate Paleozoic basement-involved tectonics in the Grenville province on the western flank of the Central Appalachian Basin.

The largest system of the four is the Rome Trough, which developed during the Early to Middle Cambrian. This system is one of the major structural elements in the region, and is part of the eastern interior system of grabens that form a major rift basin. The Rome Trough trends northeast from north central Kentucky through West Virginia and into southwestern Pennsylvania. Although the Rome Trough does not extend into Ohio, its influence on the subsurface of Ohio is significant, specifically in the southeastern part of the state. Several smaller fault systems extend into Ohio, resulting from the formation of the Rome Trough. Ammerman and Keller (1979) proposed three possible explanations for the origin of the Rome Trough: 1) Rifting above a back-arc basin in which the Rome Trough represents a zone of transform faulting. 2) The Trough may represent the failed arm of a rift at a triple junction. 3) Graben formation related to extension at the craton margin, in which the Rome Graben was oriented normal to regional opening of the Iapetus Ocean

## Petrophysics & Deposition

Coogan (1991) used the earlier work of others to divide the Clinton Interval into an Eastern, Central, and Western facies; characteristics of each are included in Table 1 (Coogan, 1991). The total interval considered contains the Queenston Shale through to the base of the Packer Shell. Total Clinton Interval thickness ranges from >200 ft in the east to < 100 feet in the west of the study area before it pinches out. Coogan (1991) identifies five main thick Clinton sand bodies: A, B, C, D, and E, (Figure 3) He also noted that maximum thickness occurs along fault traces or lineaments. For example (Figure 3) the northwest-trending Canton Lobe (C) is located between the Akron Suffield Fault and the Sugar Creek fault. The Ravenna and Suffield faults bound (D), the thick wedge of Clinton sand in southern Portage and northern Mahoning counties.

Similar structural influences have been identified in northwestern Pennsylvania in the Medina Group, Pennsylvania's equivalent of the Clinton Interval. The classifications proposed by Coogan (1991) can be useful in determining the local depositional environments of Clinton fields. If a particular facies can be determined, then its lateral extent can be determined with a moderate level of confidence.

The major source of sediments was the Taconic Highlands to the east. The interaction with the sea to the west developed local environments over the time that the Clinton Interval was deposited, creating the highly varied system of interest today. As is the case with many gas-producing sandstones in foreland basins, Lower Silurian reservoirs of the Appalachian Basin were deposited in a complex system of shallow marine to non-marine environments (Castle & Byrnes 2004).

Recent work by Castle and Byrnes (2004) provides a detailed description applicable to the Clinton Interval. In this investigation the authors determined petrophysical properties of the Lower Silurian Sandstone of the Appalachian Basin, and identified six facies: Fluvial, Estuarine, Upper ShoreFace, Lower Shoreface, Tidal Channel, & Tidal Flat. Characteristics of these facies are listed in Table 2 (Castle & Byrnes, 2004). Three additional (tables 3, 4, and 5) are included with various petrophysical and compositional data. Castle (2001) identified 3 types of sequences in the Lower Silurian siliciclastic strata of the Appalachian Basin (figure 4): coarsening upward type A, coarsening upward type B, and fining upward. He interprets the coarsening upward types A and B as representing aggradation and shoreline progradation, respectively, and the fining upward sequences as formed by transgressive infilling of incised valleys and possibly in some areas in Lowstand Alluvial bypass systems. Castle and Byrnes (2004) concluded in their work that variations in reservoir petrophysical properties of the Lower Silurian sandstones of the Appalachian Basin are directly related to facies-controlled dissimilarities in genetically associated properties, such as grain size, sorting and pore-throat size, which reflect regional processes due to sedimentation systems and tectonic setting. For example sand grain size and sorting, which determine the pore throat diameter, and influence the permeability, were controlled by the sediment distribution related to tectonic processes. This depositional setting produces reservoir trends that are characteristically difficult to predict. In addition, production from many of these sandstones is highly dependent on the petrophysical properties, which result from differences in facies, mineralogy and diagenesis (Castle and Byrnes 2004). These controls on reservoir conditions are underscored by low permeability within these sandstones.

## Natural Fractures

Natural fractures are documented or inferred in the majority of Clinton sandstone facies (Zagorski and Ryder, 2003). Fracture sets in the Clinton Interval trend both northwest and northeast, with a northeast orientation being more frequent. When formations are stimulated using hydraulic fracturing in central Ohio the path of least resistance is most commonly to the northeast. The role of natural fractures in improving the reservoir performance of the Clinton Interval has been debated. Knight (1969) proposes that most of the natural fractures are closed, cemented or otherwise sealed so that their effect on the oil and gas reservoirs of the Clinton Interval is minimized. This could be a local effect, with variations between regions. Natural fractures generally improve a formation's potential for yielding significantly higher amounts of producible hydrocarbons, although a number of variables dictate whether the fractures will improve a particular reservoir's hydrocarbon potential or not. These variables include density of the rock and fractures, porosity, orientation of the fractures, reservoir rock type, and as suggested by Knight (1969), secondary processes that can seal the fractures. Ultimately the determining factor for whether natural fractures will influence production is the method employed in development. Not fully understanding the type and orientation of the fracture set in each specific case will significantly decrease the rate of production from the formation.

## Hydrocarbon Source & Maturation

The Cabot Head formation was considered initially to be the source of hydrocarbons contained within the Clinton Interval (Knight, 1969). Analysis of this unit has since proven that the total organic carbon contained within the Cabot Head Shale is not sufficient for the accumulation present in the Clinton Interval. It is possible that a portion of the hydrocarbons could have been derived from this section, but recent work has argued that the majority of the hydrocarbons have come from the Point Pleasant Formation (Drozd and Cole 1994). These authors also state that the White Water Formation and the Knox Dolomite are also possible hydrocarbon source rocks for the Clinton Interval.

Reservoir rocks that produce oil in Ohio range in age from Cambrian to Pennsylvanian. Hydrocarbon migration is typically in the updip direction; however downdip migration does occur in some hydrocarbon systems. The Clinton Interval is capped by the Salina Group, a thick unit of evaporite beds which act as a stratigraphic seal, separating the upper Paleozoic oil from the lower Paleozoic oil that is contained in the Clinton Interval. Drozd and Cole (1994) used stable carbon isotopic composition of oil and kerogen pyrolyzates to correlate hydrocarbons in the Point Pleasant source rock with the hydrocarbons in the lower Silurian trap rock. Based on 150 measurements from core and drill cuttings taken throughout Ohio, the Point Pleasant Formation averaged 1.3% TOC & 3.94 Kg Hc/t rock (Drozd and Cole, 1994). Qualitative techniques used to evaluate the Point Pleasant Formation include: Thermal alteration index, conodont color alteration index, qualitative fluorescence, and transformation ratios (S1/ (S1+S2) from rock pyrolysis) (Drozd and Cole, 1994). The least mature area of the Point Pleasant Formation lies along the Cincinnati-Findlay Arch. The portions that reached the deepest depths and hence experienced the largest amounts of pressure and heat are the most mature, so that maturity increases toward the southeast into the Appalachian Basin.

Burial history and hydrocarbon generation models suggest that most oil and gas was generated & expelled from the Point Pleasant Formation during the Late Devonian/Early Mississippian for central & southwestern Pennsylvania, and during the Late Pennsylvania/Permian for western West Virginia and eastern Ohio (Ryder & Zagorski, 1999). Drozd and Cole (1994) suggest that the critical time for hydrocarbon generation from the Point Pleasant Formation occurred when it was buried at its greatest depth of 3.4 km during the Triassic (230mya). The critical moment is when the freshly generated oil and gas have migrated and accumulated in the nearest trap. If uplift and severe deformation follow this event, then much of the hydrocarbon will be destroyed or released to migrate to another trap.

Drozd and Cole (1994) suggest that the source rocks of the Lima-Indiana trend are part of a different petroleum system from the Michigan Basin, rather than part of the Point Pleasant system. Ryder et al (1998) suggested that the Point Pleasant system charged the Lima-Indiana field as well as the majority of fields in Ohio, including up to the Clinton Interval, as the hydrocarbons migrated updip after maturation. The isotopic similarities of the hydrocarbons throughout the basin indicate similar origin from the Point Pleasant source. Ryder et al (1998) propose that the Lima-Indiana trend could include hydrocarbons from other sources, but conclude that a significant portion was derived from the Point Pleasant. Estimates of recoverable gas reserves within the Clinton/Medina groups of Ohio, Pennsylvania, and a small portion of West Virginia range from 8.2 to 94 tcf. The U.S. Geological Survey estimated 30.3 tcf of undiscovered recoverable gas (1996). Ryder et al(1998) suggest that the gas to oil ratio within the Lower Clinton Interval will increase significantly as a result of this large gas reserve that remains to be produced. The majority of these reserves will come from the Basin-Center (Figure 5) portion of the Appalachian basin. Drozd and Cole (1994) estimated the hydrocarbon reserves of the Clinton sandstones at less than 60bbl of oil or 250 mcf of gas/ac-ft with net pay typically being less than 20ft.

## Case study

Four hundred and thirty well completion well logs within Harrison, Butler, Jackson, and Clay townships of Knox County, Ohio, were collected from the Ohio Geological Survey for analysis. The study area is shown in Figure 6. Information obtained includes depth of top and bottom contacts for the Packer Shell and Clinton

Sandstones, elevation of ground surface, and location coordinates. A moderate level of uncertainty can be expected due to inconsistencies among the many different drillers that completed the wells in this area. Preliminary screening of the data was completed to identify and remove extreme outliers within the data set. The result is a relatively smoothed data set, which yields a reasonable depositional interpretation over this region. Structural interpretations for this study are highly subjective, based on accuracy of maps created, constrained by the distribution and quality of data, and by the lack of methods for obtaining additional data to correlate with the depositional interpretations.

Oil, gas and brine production data was also collected from the Ohio Geological Survey. A major limitation on this study arises from the absence of production data prior to 1984 in most cases. As a result, this data represents a small fraction of what actually has been produced since this area's first well was drilled at the beginning of the 20$^{th}$ century. Based on conversations with individuals familiar with the development of the study area the author is confident that the most productive wells in this area have not been identified because of this lack of data. The production data included was also screened for anomalously high or low values. One organization in particular provided data that appeared suspect for one year’s production in more than one case; this data was removed. Most wells that were moderate to outstanding producers followed a similar pattern of production decline over time. Wells producing into the same tank for sale were accounted for, by stripping the more recently drilled, in most cases the wells were moderate producers.

Maximum water production for one well over this entire area is limited to 7500 bbl in greater than a fifteen-year period. The author infers that the reservoir main drive mechanism in this area is a solution gas drive system, based on water to hydrocarbon production ratio and reservoir parameters. Typical 5-25% STOIIP (Stock Tank Oil Initially In Place) is achieved from primary production of solution gas drive system. Two locations within the study area were selected for detailed analysis, based on oil production. The fields will be referred to as East and West (Figure 7). As stated earlier lack of sufficient production data prevents accurate evaluation of the overall performance of this reservoir system. Cumulative production for these two pools is 400,000 BO and 700,000 MCFG from the data available since 1984, however these represent minimum production overall.

A major factor affecting production in this study area is method of completion. Only wells since the 1950s were HydroFraced, wells completed before this time are a minority in this study. Completion techniques for this minority were dominated by nitro glycerin stimulation, a method that had as many negative completion effects as positive. The majority of wells completed before 1974 were HydroFraced with open hole completion (casing only being run to the top of the first producing horizon). Wells completed since 1974 were almost completely HydroFraced with either open hole or perforated (casing run completely to bottom perforations in suspected producing horizons) completion. The method of completion may have greatly decreased the production as a result of the complexity and lack of knowledge for the Clinton Interval. The most widely used technique today is perforated completion; this technique proves to be the most effective stimulation method performed in the Clinton Interval.

The data set was analyzed with Surfer contouring and mapping software by Rockware. Kriging was used to grid the data; this process involves estimation of a regionalized variable: depth below sea level, thickness, and production. This method introduces some uncertainty into the interpretation; the lowest levels of uncertainty are in areas where the data points are most evenly spaced. Numerous preliminary maps were constructed in order to refine the data set and identify & remove outliers. Well spot maps available at the Ohio Geologic Survey were used to correlate data locations of the created maps in this study. Some wells in the data set with no location coordinates were estimated using the digitize tool in surfer and are included.

## Mapping (Entire Area)

The Clinton reservoir system is difficult to map as a result of its complex geology, combined with irregular distribution of wells drilled during development of this area. Elevation maps for the top and bottom contacts of the Packer Shell and the Clinton Sandstone were constructed, (Figures 8, 9, 10, 11). As expected for this area of the Appalachian Basin; depths of these horizons increase from west to east. This regional trend produces a drop of over -300ft across the entire study area west to east.

Net unit thickness maps for both the Clinton Sandstone and Packer Shell were constructed using the descriptive well logs. The Packer Shell (Figure12) is more easily and accurately represented because of its more uniform distribution than the Clinton Sandstone. The average thickness of the Packer Shell is 26ft with a maximum and minimum of 44 & 10ft, respectively. The net sand value for the Clinton Interval (figure 13) is the cumulative sand (all bodies) for each data point, and averages net thickness of 40ft, with a maximum and minimum of 85 & 10ft, respectively.

## West Field

One hundred of the data points were included in the West Field (Figure 7). Elevation maps for the Packer Shell, 1st and 2nd Clinton Sandstones were constructed, (figures 14, 15, 16, 17). Accumulative oil and gas production since 1984 for this area is over 200,000 BBL & 400,000 MCF, respectively. Most wells in this area were drilled since the late 1970s; the most productive on record occur in the middle of this field (figure 18), they also contact a 2nd Clinton Sandstone. Completion records for the most productive wells lack accurate completion data, (e.g. whether one or both sands were stimulated). However, a correlation between most productive wells and contact with the 2nd Clinton Sandstone can be made. Mapped in Figure 18 is net thickness of the 1st Clinton Sandstone, and figure 19 shows wells in that same area that contact the 2nd Clinton Sandstone. If the majority of production is from the second sand, then the shale break between it and the first must have been an effective seal for this reservoir system. Wells 3850, 3854, 3828, 1605, 2722, 3832, 2590 (Figure 18), seem to show a terminus of the 2nd Clinton sand body. Production data correlate with this terminus for sharp decrease in production (Figures 22 and 23).

Figures 20 and 21 show the top and bottom contacts, respectively, of the 2nd Clinton sandstone. Although complicated by irregularly spaced data, Figures 20 & 21 show some indication of a structure trending northwest-southeast located in top east corner, defined by wells 1982 and 1553. This structure is a lobe of the 2nd Clinton Sandstone that appears deeper than its surroundings.

Figure 24 gives the cross section lines for the West Field. Cross sections 1 and 2 (figures 25 and 26) extend the correlation for a structure listed above. Figure 26 illustrates what appears to be a drop down structure between 2056000 and 2058000, possibly a fault, running east-west through the suspected terminus. Cross section 3 (Figure 27) shows a less pronounced structure at 242325 than the structure illustrated in cross section 2 at 242000. Cross section 4 (Figure 28) is south of this structure, line of cross section running at 241140. The proposed structure doesn't appear to extend into this cross section. Proximity suggests that any tectonic influences on this area were caused by the Cambridge-Burning Springs and/or related Parkersburg Loraine fault system. Orientation of proposed fault would run northwest-southeast, nearly parallel to the strike of the Cambridge-Burning Springs system.

Figure 29 illustrates net thickness of the Packer Shell; average thickness in this area is 28 feet, with a minimum and a maximum of 18 and 40 feet, respectively. Variation in thickness of this unit corresponds moderately with thickness changes in the underlying Clinton Sandstone.

## East Field

Seventy seven data points were included in the East Field. Data for accumulative oil and gas production gives a minimum of over 200,000 BBL and 300,000 MCF, respectively. A large number of wells were drilled to the east and to south of the southeastern part of this field (Figure 30) prior to 1970, which indicates an area of high production, because of high well completion cost (specifically casing cost) coupled with low oil and gas prices prior to 1970. Well spot maps provided by the Ohio Geological Survey list incredibly high initial production values for these earlier wells, compared with initial production values for the entire study area. These areas to the east and south of the

East Field must have been highly productive in the past. Unfortunately no stratigraphic or production records were available.

More recent development of this field by Reliance Energy (Figure 30) has provided the stratigraphic and production data for this section of interest. Well 3863 (Figures 31 and 32) drilled in 1989 was the most productive of the new wells. This well was HydroFraced and completed with perforations through the 53 feet section of assumed sand. Similar to the West Field, lack of sufficient completion data limits characterizing beyond reasonable doubt which Clinton Sandstone, upper or lower, or both produced the hydrocarbons.

Figure 33 details the lines of cross section through the east field. Cross section 1 (Figure 34) correlates a structure with high production values (Figure 31). A drop of 14 feet between well 3863 and 1739 also appears to be a barrier of production, even though the wells share similar top sand thicknesses. Well 3863 makes no contact with the 2$^{nd}$ Clinton Sandstone; well 1739 makes contact with the 2$^{nd}$ Clinton Sandstone separated from the 1$^{st}$ by 15 feet shale break. Well 3858 has a 13 feet shale break between Clinton Sands 1 and 2; well 3883 has no contact with a second sand. Both wells were perforated again records lack accurate data for intervals of perforations. Even with a 13 feet shale break for well 3858, it and 3883 have the same net sand within 2 feet. The area of most production lies within a topographic high of the Packer Shell below sea level, which trends northeast-southwest. Cross section 2 (Figure 35) provides little information. Cross section 3 (Figure 36) depicts the thinning of the 1$^{st}$ Clinton Sandstone and a dip in the units at 2071000. Elevation maps for the Packer Shell and Clinton Sandstones 1 & 2 (Figures 37, 38, 39, 40, 41, 42) are included. Correlation with these maps is stymied by lack of sufficient production and completion data. Net thickness of the Packer Shell (Figure 43) in most areas correlates with the underlying Clinton Sandstone. Thin values of net Clinton Sand are paired with moderate to thick values of Packer Shell.

## Conclusions

This study proves that the information presented from the data collected is only valuable as a way to correlate more concrete and scientifically obtained sources of data. Reservoir characterization of the Clinton Interval is very complicated. This Interval records a complex system of deltas, river/tidal channels, and other associated structures, further affected by tectonic influences. The fractionated manner and time of development for this portion of the Appalachian Basin has significantly reduced its overall STO (Stock Tank Oil) recovery factor from primary production. Methods of well completion being of substantial importance. Zones not properly identified before completion may kill a well before its brought on line. Iron rich zones disregarded during well completion can and have proven to become insoluble when treated with some types of hydrofracing acid. Instead of improving porosity and permeability within the vicinity of the borehole, natural and hydraulically induced fractures can be sealed off.

The work presented here is incomplete. Further characterization of this reservoir with the implementation of a successful secondary recovery pilot is possible. Delineating small scale tectonic structures that may have provided the infrastructure for the accumulation of hydrocarbons is crucial. Borehole seismic and Geochemical tracers provide economically feasible methods for accurately characterizing and mapping this field. Understanding the pathways through which the hydrocarbons migrated from their source can lead to the discovery of untapped pools within the basin. Further exploration within the Appalachian Basin remains. More importantly millions of barrels of discovered oil remain, to be recovered.

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9) Root, Samuel & Onasch, Charles M. Structure & Tectonic Evolution of the Transitional region between the central Appalachian Foreland & Interior Cratonic Basins. Tectonophysics Vol 305 Issue (1-3) 1999 pp 205-223

10) Ryder, Robert T., Burruss, Robert C., Hatch, Joseph R. Black shale Source rocks of Oil Generation in the Cambrian & Ordovician of the Central Appalachian Basin, USA. AAPG Bulletin Vol 82 no 3 March 1998 pp 412-441

11) Ryder, Robert T & Zagorski, William, Nature Origin & Production characteristics of the lower Silurian regional Oil & Gas accumulation, central Appalachian Basin, United States. AAPG Bulletin V. 87 no 5, May 2003 pp 847-872

12) Samuel I. Root, 1958 Geology of Knox County, Ohio. Dissertation, The Ohio State University

13) Wickstrom, L.H., A new look at the Trenton (Ordovician) structure in northwestern Ohio: Northeastern Geology, 1990 v. 12 p. 103-113.

14) Zagorski, William Regional Trapping styles in the "Clinton" Medina Sandstone Group Appalachian Basin. Ontario Petroleum Institute V. 38 1999 pp 1-34

Figure 1 (Drozd and Cole 1994)

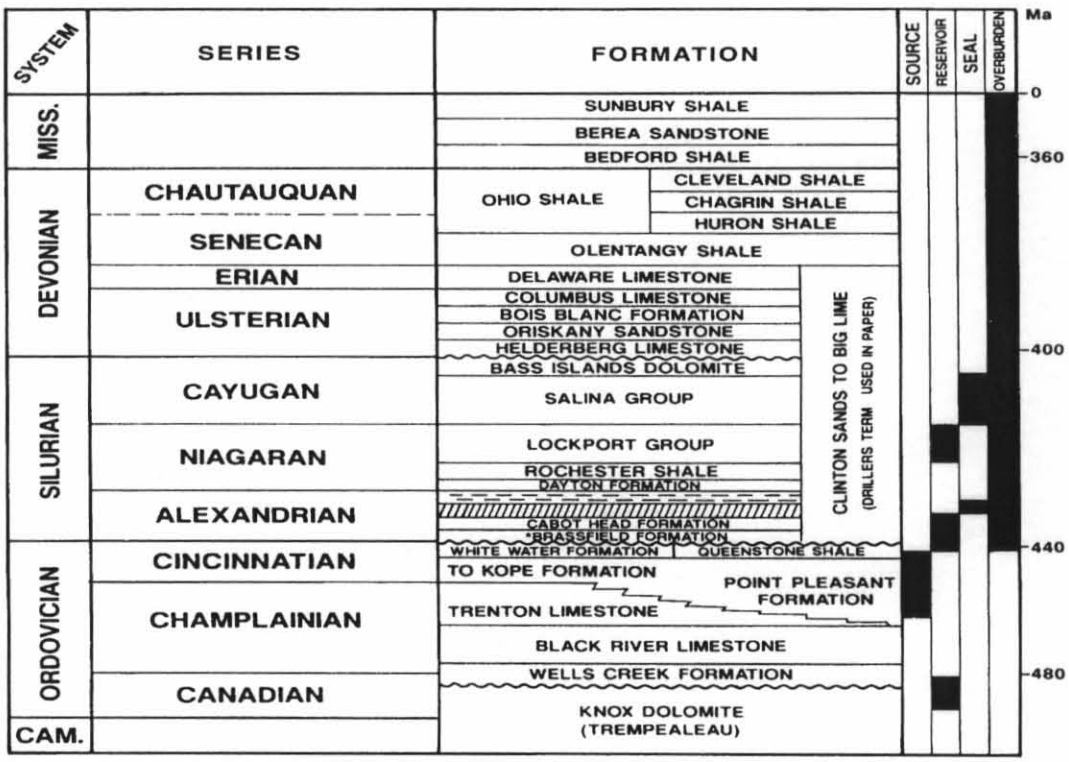


**Figure 2 (Root and Onasch 1999)**

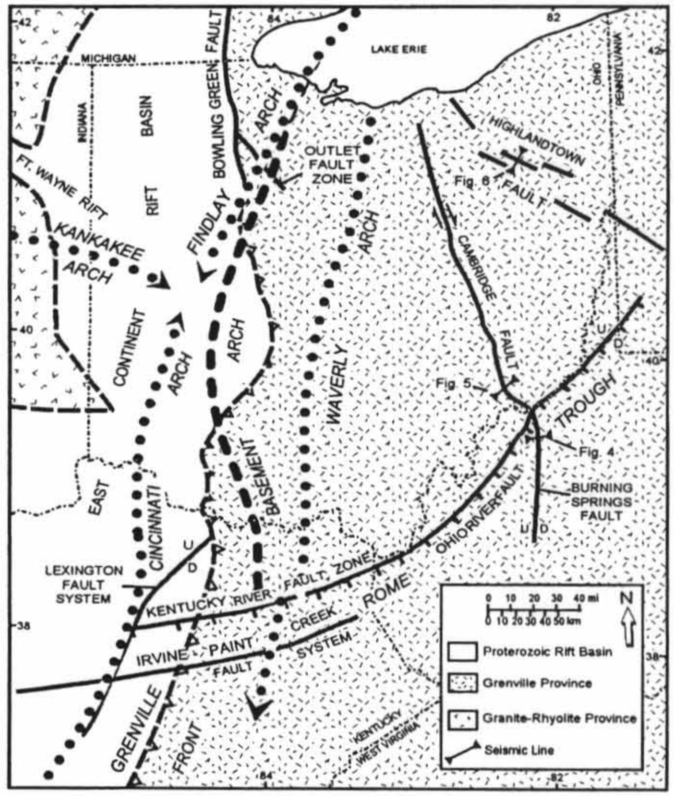


Table 1
Coogan 1993

| UNIT | WEST | CENTRAL | EAST |
|---|---|---|---|
| Total Interval Thicknes | 110-130 | 160-180 | 180-210 |
| Base of Packer Shell | Dolomite | Either | High Density, Fe-Rich Zone |
| Stray Clinton | Carbonate | Porous Sandstone | Porous Sandstone or Shale |
| Main Clinton Sandstones (Red and White) | Thin Variable | Thin and Thick | Thick Less Variable |
| Cabot Head Shale | With HD, Fe-Rich beds | Calcareous Shale | Shale |
| Whirlpool | Dolomitic Shale or Manitoulin Dolomite | Limestone, or calcareous Shale | Porous Sandstone (locally shaly) |

Figure 3
Coogan 1993
Thickness in feet

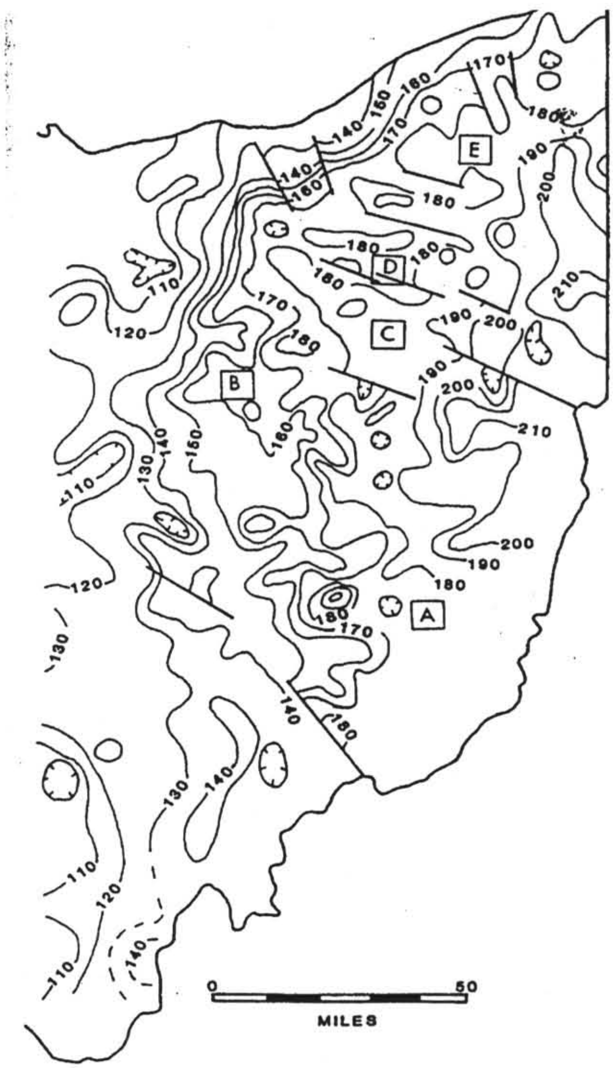


**Table 2 (Castle and Byrnes 2004)**

Characteristics of Lower Silurian Sandstone Facies (Appalachian Basin) for which Petrophysical Properties Were Measured

| Facies | Lithology | Bedding | Primary Sedimentary Structures | Other Features |
|---|---|---|---|---|
| Fluvial | predominantly fine- to coarse-grained sandstone, minor pebbles concentrated in layers and lenses; pale yellow, white, and light gray; minor interbedded gray mudstone | medium- to thick-bedded | common trough and planar cross-bedding; scoured basal contacts; common shale rip-up clasts | sandstone beds commonly fine upward, sometimes into mudstone; sandstone beds are commonly stacked into thick sequences; burrows are absent |
| Estuarine | predominantly fine- to coarse-grained sandstone, minor granules and pebbles concentrated in layers and lenses; pale yellow, white, and light-medium gray; minor interbedded gray mudstone | thin- to thick-bedded | common sigmoidal and planar cross-bedding, sometimes bidirectional; shale drapes and couplets on foresets; basal contact commonly erosional; common shale rip-up clasts | tops of sandstone beds are sharp to gradational into mudstone; minor to common vertical and horizontal burrows |
| Tidal channel | predominantly very fine- to fine-grained sandstone, minor medium- to coarse-grained sandstone; red in hematitic intervals, green to greenish gray in chloritic intervals; common interbedded gray and greenish gray mudstone | thin- to medium-bedded; minor thick-bedded | common trough cross-bedding, bidirectional cross-bedding, reactivation surfaces, and shale drapes on foresets; minor shale couplets on foresets; sharp, basal contacts commonly erosional; common shale rip-up clasts | multiple fining-upward sandstone beds form overall coarsening-upward intervals; minor, small horizontal and vertical burrows; sparse phosphatic brachiopods |
| Tidal flat | very fine- to fine-grained sandstone interbedded with mudstone and siltstone; predominantly hematitic and red, minor gray | thin- to medium-bedded | common current-ripple lamination; small-scale bidirectional cross-bedding; wavy bedding | common vertical burrows; bioturbation commonly obscures primary physical structures; sandstones are commonly argillaceous |
| Lower shoreface | predominantly very fine-grained sandstone; minor fine-grained sandstone; light-medium gray and greenish gray; minor mudstone interbeds | thin- to medium-bedded | common wave-ripple cross-lamination | common to minor small, horizontal burrows; sparse to minor fragments of phosphatic brachiopods; minor glauconite |
| Upper shoreface | fine- to medium-grained sandstone, minor coarse-grained sandstone; light-medium gray, greenish gray, and white; rare to minor gray mudstone interbeds and interlaminae | medium- to thick-bedded | common horizontal lamination and low-angle cross-lamination; minor wave-ripple cross-lamination | sparse small, horizontal burrows; sparse fragments of phosphatic brachiopods |

## Tables 3, 4, & 5 (Castle and Byrnes 2004)

. Composition of Depositional Facies Determined by Point-Counting of Thin Sections (300 Points per Thin Section)*

| | Number of Samples | Detrital Grains | Matrix | Cement | Porosity |
|---|---|---|---|---|---|
| Estuarine | 16 | 56.3 (46.3–65.3) | 2.0 (0.0–10.7) | 32.0 (22.0–41.7) | 9.6 (4.7–18.3) |
| Fluvial | 23 | 52.7 (44.0–70.0) | 0.4 (0.0–5.0) | 32.4 (19.7–42.7) | 14.5 (4.3–17.7) |
| Lower shoreface | 14 | 52.2 (42.7–64.6) | 3.0 (0.0–17.7) | 36.5 (23.0–51.3) | 8.3 (4.0–14.7) |
| Tidal channel | 21 | 55.7 (46.0–64.6) | 1.9 (0.0–7.0) | 34.0 (24.0–41.7) | 8.3 (3.0–13.7) |
| Tidal flat | 11 | 60.8 (52.3–72.0) | 8.2 (0.0–23.3) | 28.7 (16.0–41.3) | 2.4 (0.0–6.0) |
| Upper shoreface | 30 | 53.7 (39.0–63.3) | 0.4 (0.0–4.7) | 31.6 (18.7–48.7) | 14.3 (10.0–19.7) |

*Arithmetic average percent (and range) is listed.

Quartz-Feldspar-Lithic (QFL) Composition of Detrital Grains Determined by Point-Counting of Thin Sections (300 Points per Thin Section)*

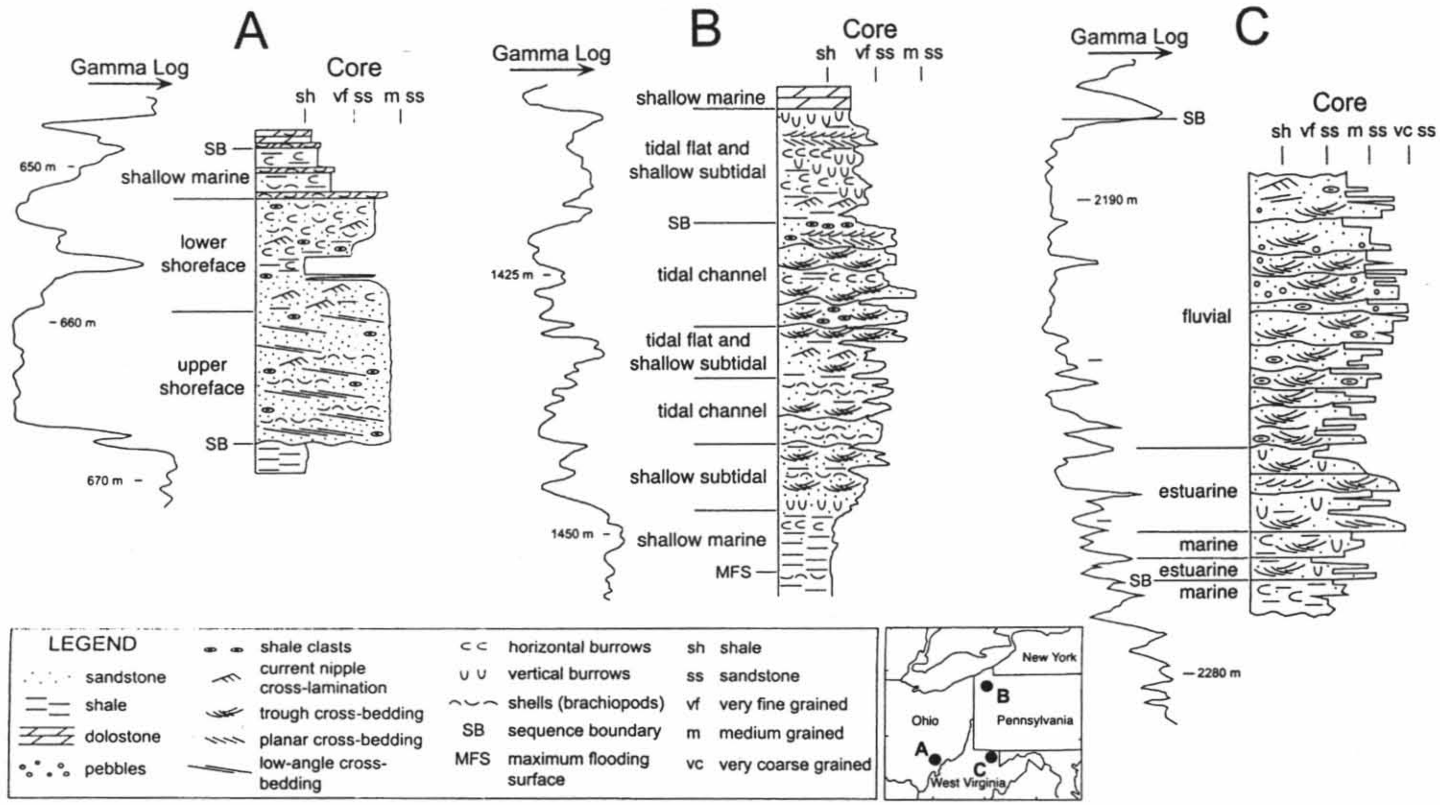
| | Quartz | Feldspar | Lithic |
|---|---|---|---|
| Estuarine | 94.0 (78.9–100.0) | 0.7 (0.0–1.8) | 5.3 (0.0–21.1) |
| Fluvial | 95.4 (87.7–100.0) | 0.9 (0.0–6.1) | 3.7 (0.0–12.3) |
| Lower shoreface | 83.0 (64.1–97.5) | 16.2 (2.5–34.7) | 0.9 (0.0–4.3) |
| Tidal channel | 72.4 (57.0–93.5) | 24.6 (6.5–40.3) | 3.0 (0.0–9.0) |
| Tidal flat | 65.4 (49.1–77.8) | 31.8 (22.2–50.9) | 2.8 (0.0–10.2) |
| Upper shoreface | 85.9 (66.4–96.9) | 13.1 (3.1–28.8) | 1.0 (0.0–4.8) |

*QFL composition is normalized to 100%. Arithmetic average percent (and range) is listed.

Cement Content as a Percentage of the Total Rock Volume Determined by Point-Counting of Thin Sections (300 Points per Thin Section)*

| | Quartz Overgrowth | Chlorite | Hematite | Dolomite | Anhydrite |
|---|---|---|---|---|---|
| Estuarine | 17.8 (8.0–26.3) | 7.5 (1.0–21.3) | 4.2 (0.0–11.0) | 2.5 (0.0–10.0) | 0.04 (0.0–0.7) |
| Fluvial | 14.8 (6.7–20.0) | 15.8 (0.0–20.7) | 1.2 (0.0–9.3) | 0.1 (0.0–1.0) | 0.5 (0.0–10.7) |
| Lower shoreface | 14.3 (9.7–19.0) | 11.1 (5.7–14.3) | 1.1 (0.0–6.7) | 9.5 (0.0–28.0) | 0.4 (0.0–2.0) |
| Tidal channel | 15.1 (10.3–18.3) | 9.0 (1.3–15.3) | 4.7 (0.0–20.3) | 3.7 (0.0–16.0) | 1.5 (0.0–5.7) |
| Tidal flat | 13.1 (6.7–22.7) | 4.8 (0.0–15.3) | 6.8 (0.0–16.7) | 2.7 (0.0–15.3) | 1.3 (0.0–5.0) |
| Upper shoreface | 10.7 (4.7–22.0) | 10.3 (2.7–17.0) | 0.5 (0.0–2.3) | 10.1 (2.0–29.3) | 0.0 (0.0–0.0) |

*Arithmetic average (and range) is listed.




Core descriptions and gamma-ray geophysical logs. (A) Fining-upward sequence with upper shoreface and lower shoreface sandstone facies. This sequence is interpreted as having formed during transgressive filling of incised topography. Medina Group, Fairfield Co., Ohio, well 12,273. (B) Coarsening-upward sequence (type B) dominated by tidal deposits of a progradational shoreline. Medina Group, Crawford Co., Pennsylvania, well 20,665. (C) Coarsening-upward sequence (type A) interpreted as aggradational fluvial and estuarine deposits. Tuscarora Sandstone, Preston Co., West Virginia, well 119. The sequence types and their origin were discussed in greater detail by Castle (2001a).

**Figure 4 (Castle 2001)**

**Figure 5 (Ryder and Zagorski 2003)**

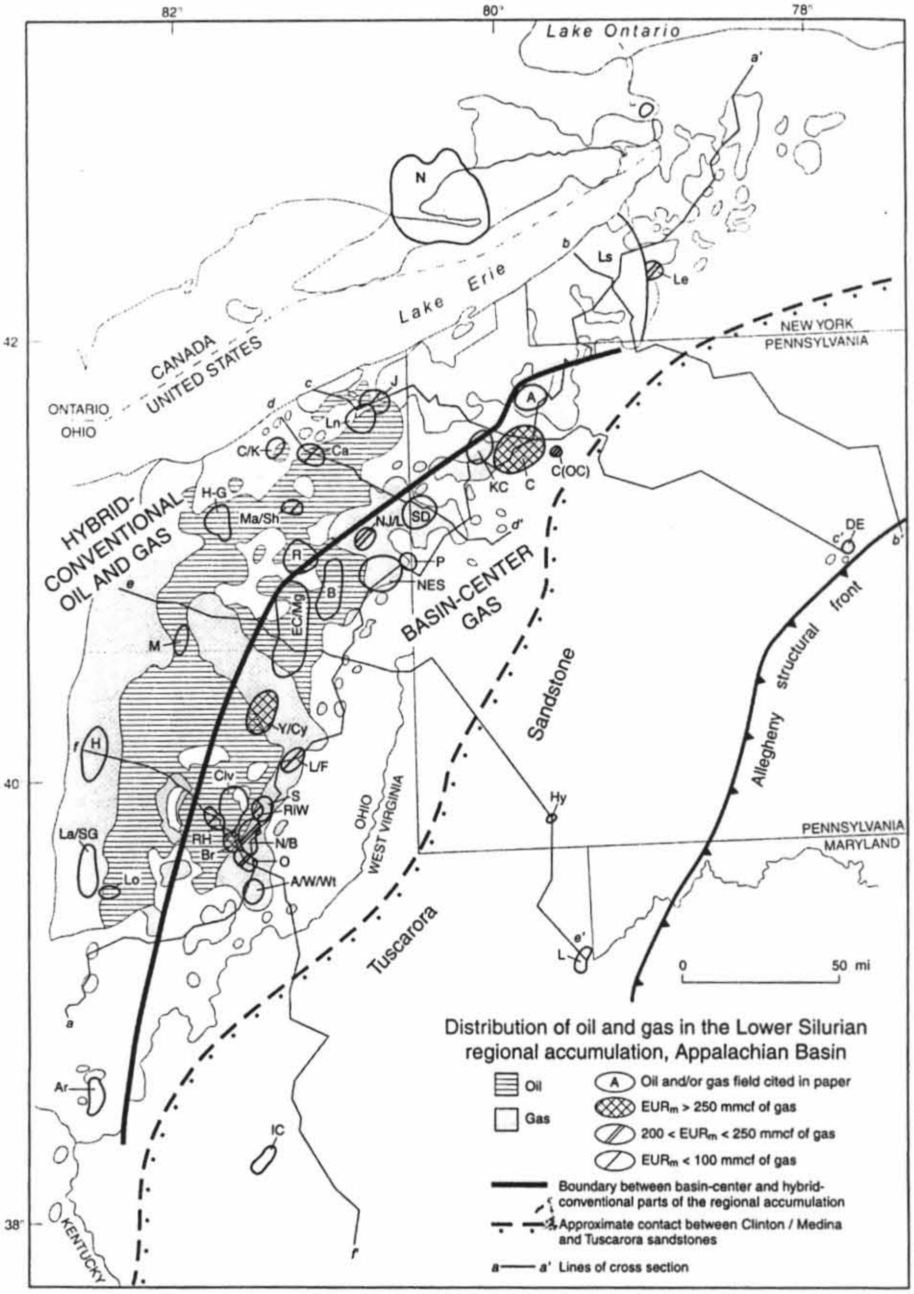


Figure 6


Region of Study
Holmes
Morrow
Knox
Coshocton
Delaware
Licking
Franklin
Muskingum
Miles
0
12.5
25
50
75
100

**Figure 7**

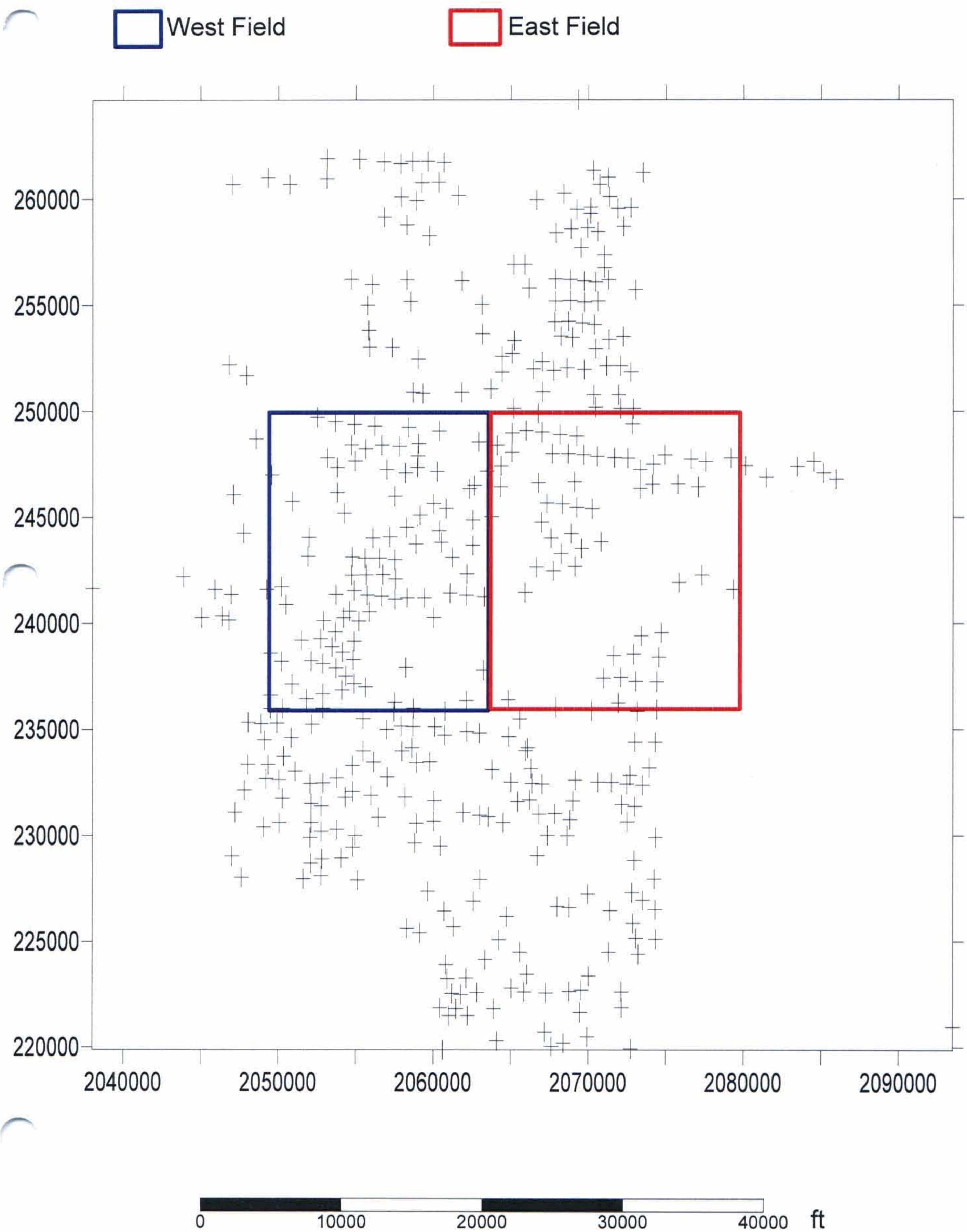
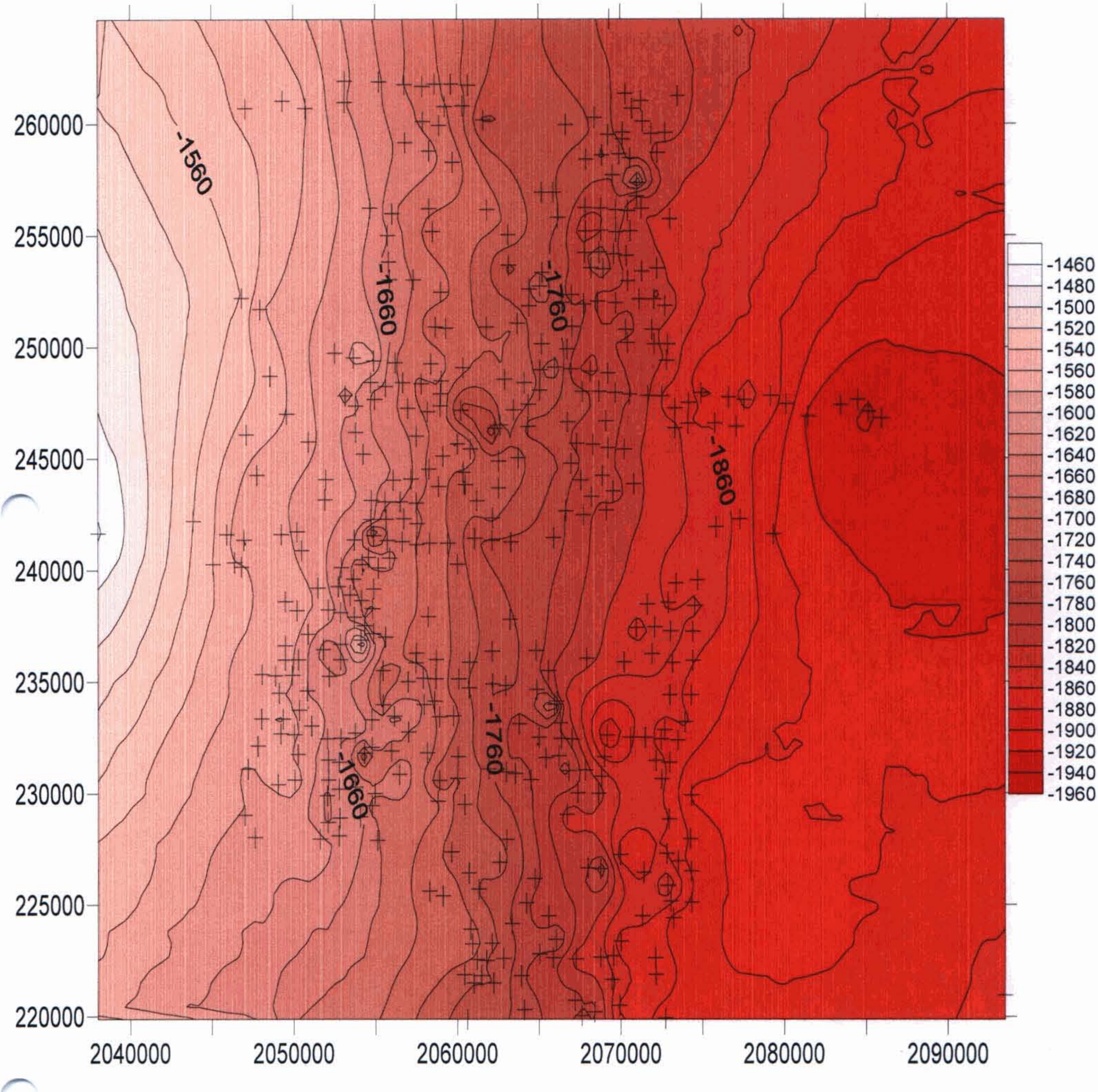

West Field
East Field
260000
255000
250000
245000
240000
235000
230000
225000
220000
2040000
2050000
2060000
2070000
2080000
2090000
0
10000
20000
30000
40000
ft

**Figure 8**

Top of the Packer Shell below sea level




C.I. 20 ft

**Figure 9**

Bottom of Packer Shale below Sea Level

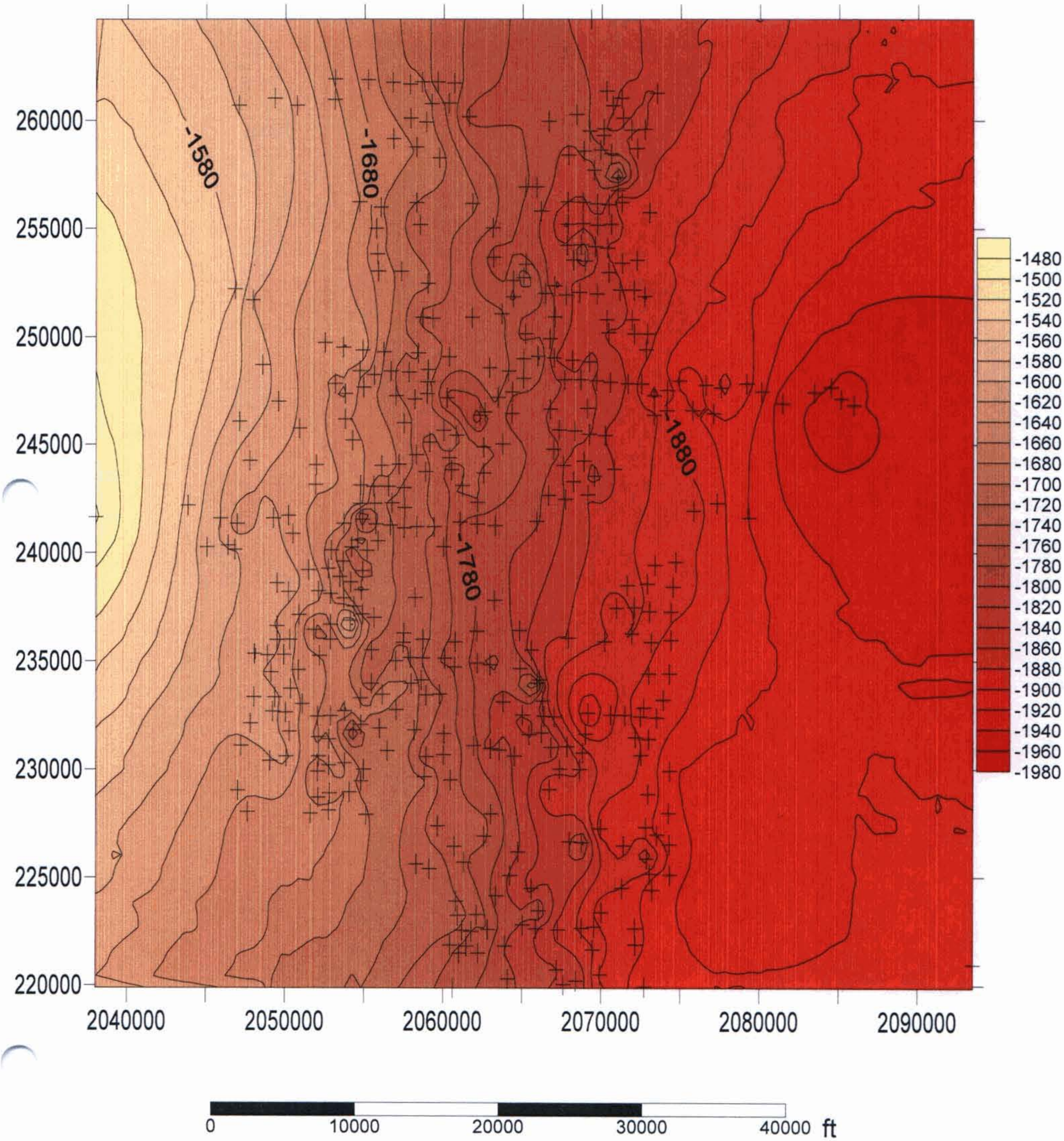
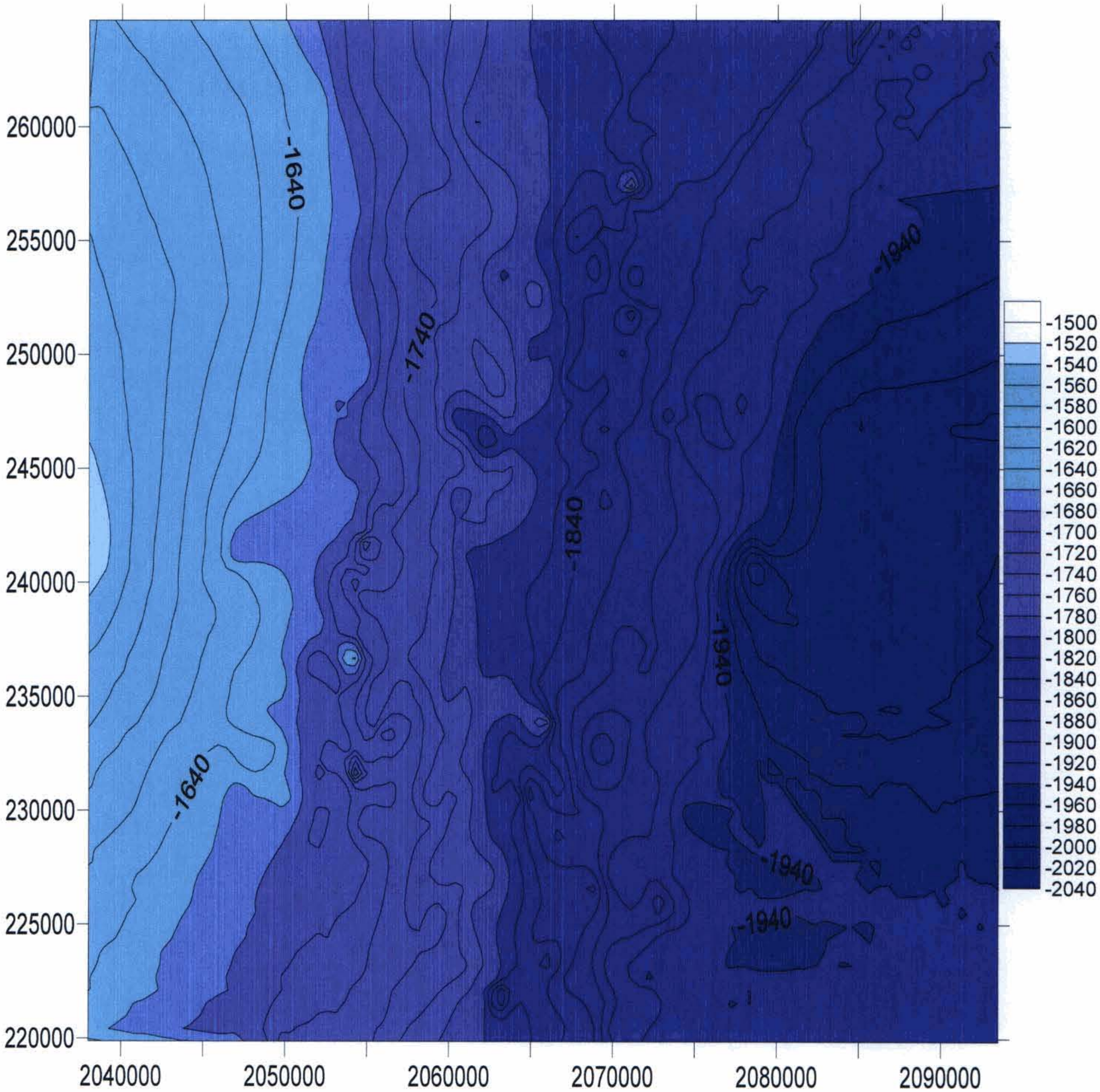


**Figure 10**

Top of the Clinton below sea level




0 10000 20000 30000 40000 ft

**Figure 11**

Bottom of Clinton Sand (below sea level)

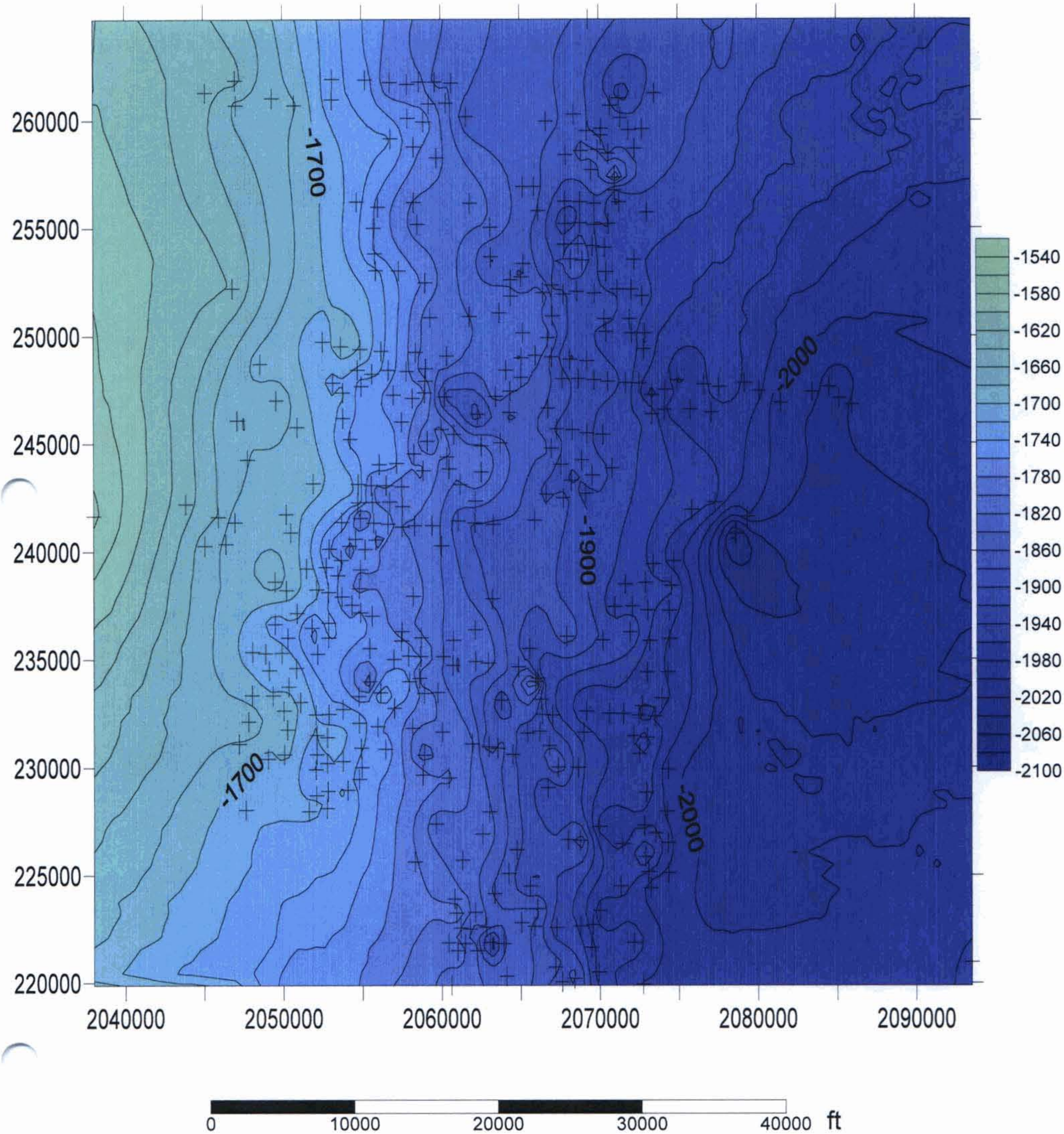


**Figure 12**

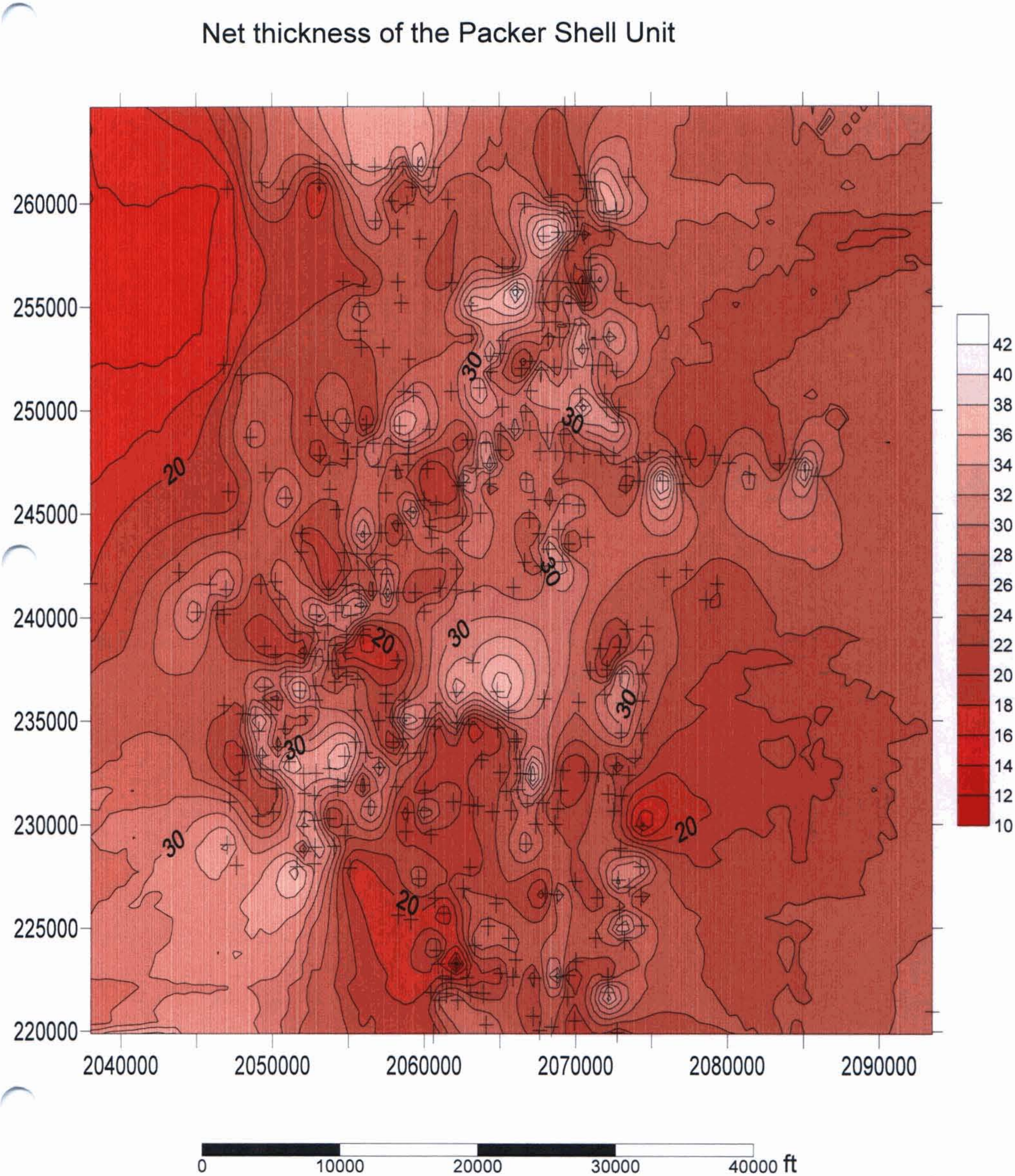

Net thickness of the Packer Shell Unit
260000
255000
250000
245000
240000
235000
230000
225000
220000
2040000
2050000
2060000
2070000
2080000
2090000
20
30
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
0
10000
20000
30000
40000 ft

**Figure 13**

Net Thickness of the Clinton Sandstone

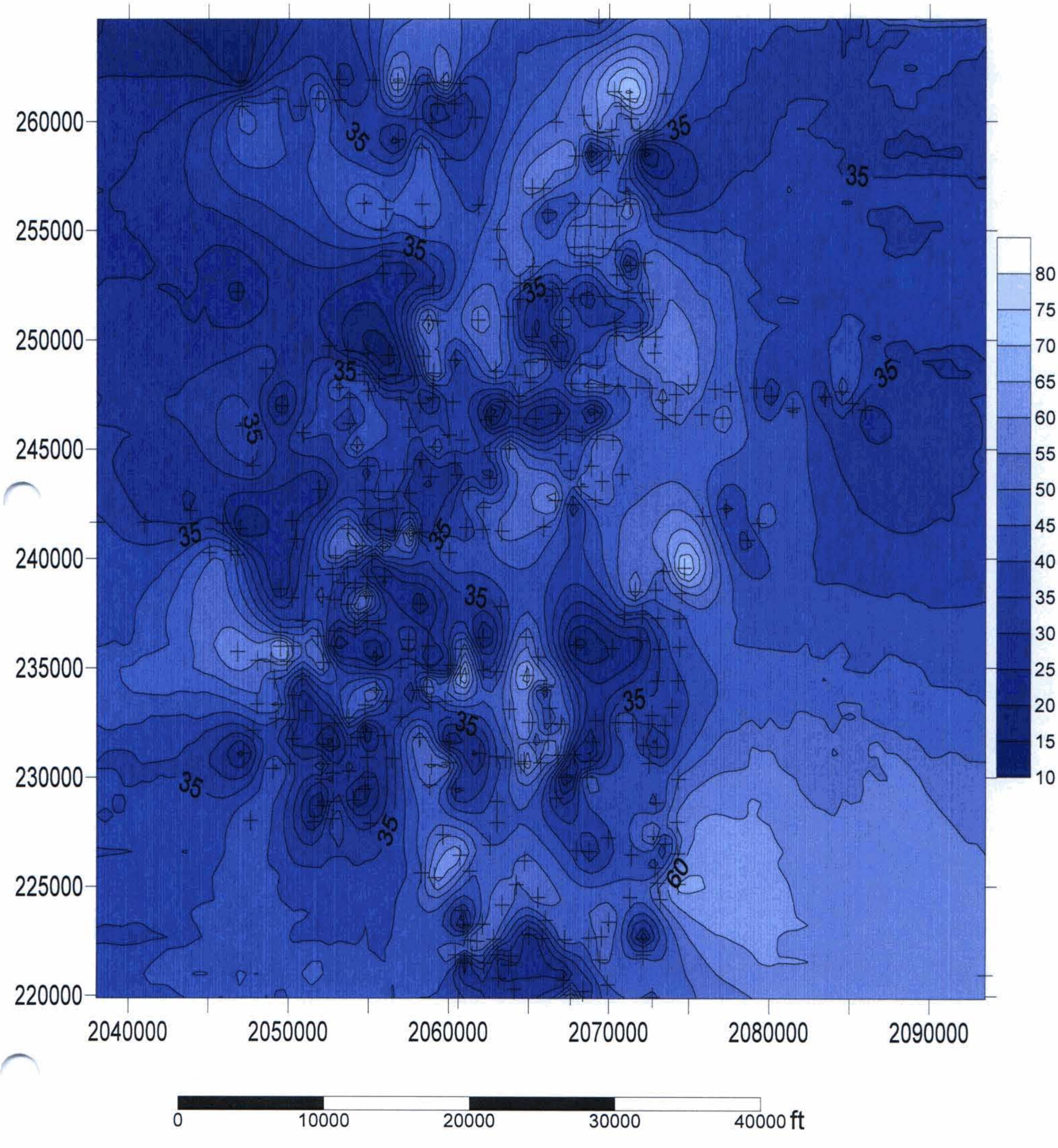


**Figure 14**

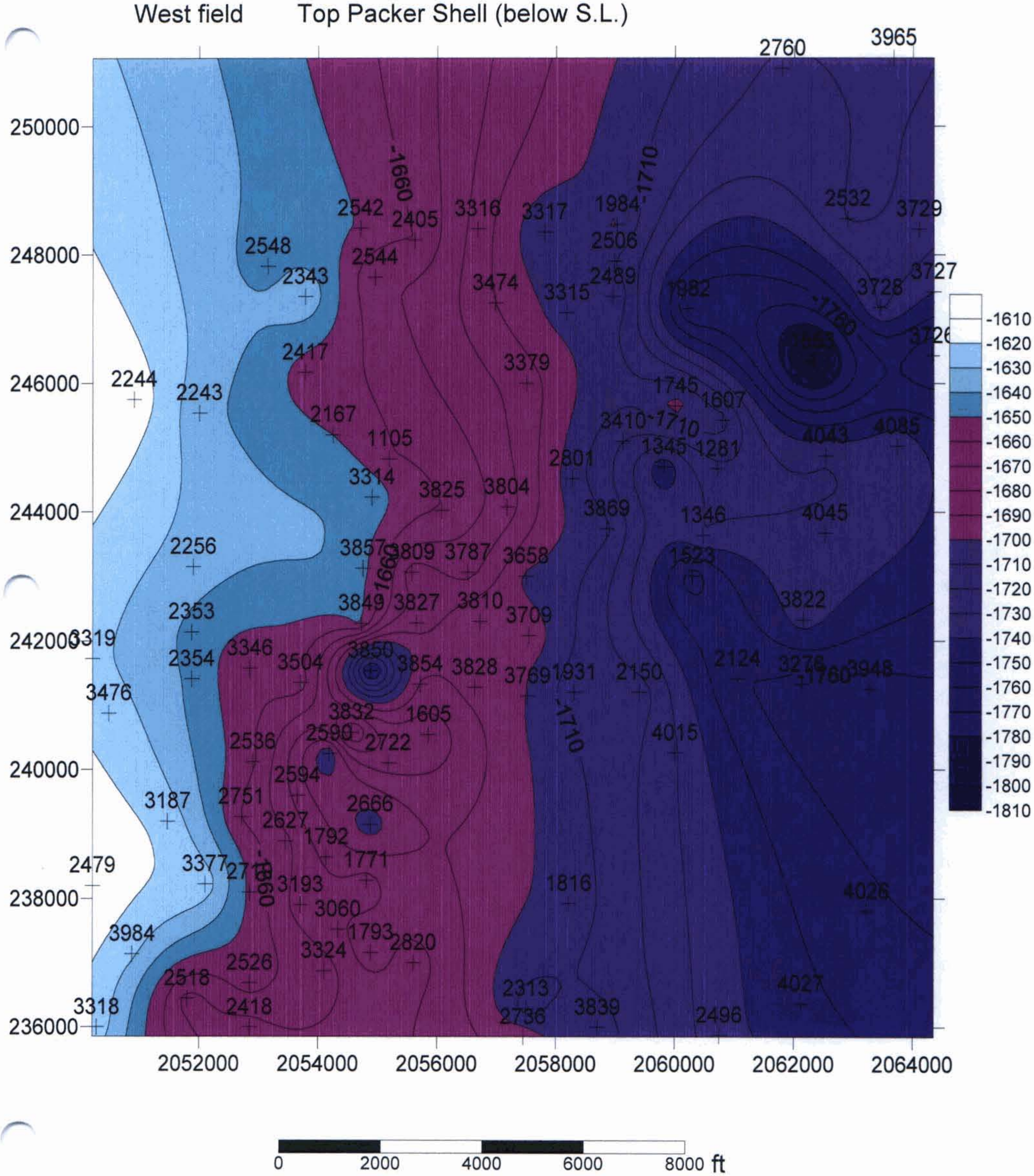
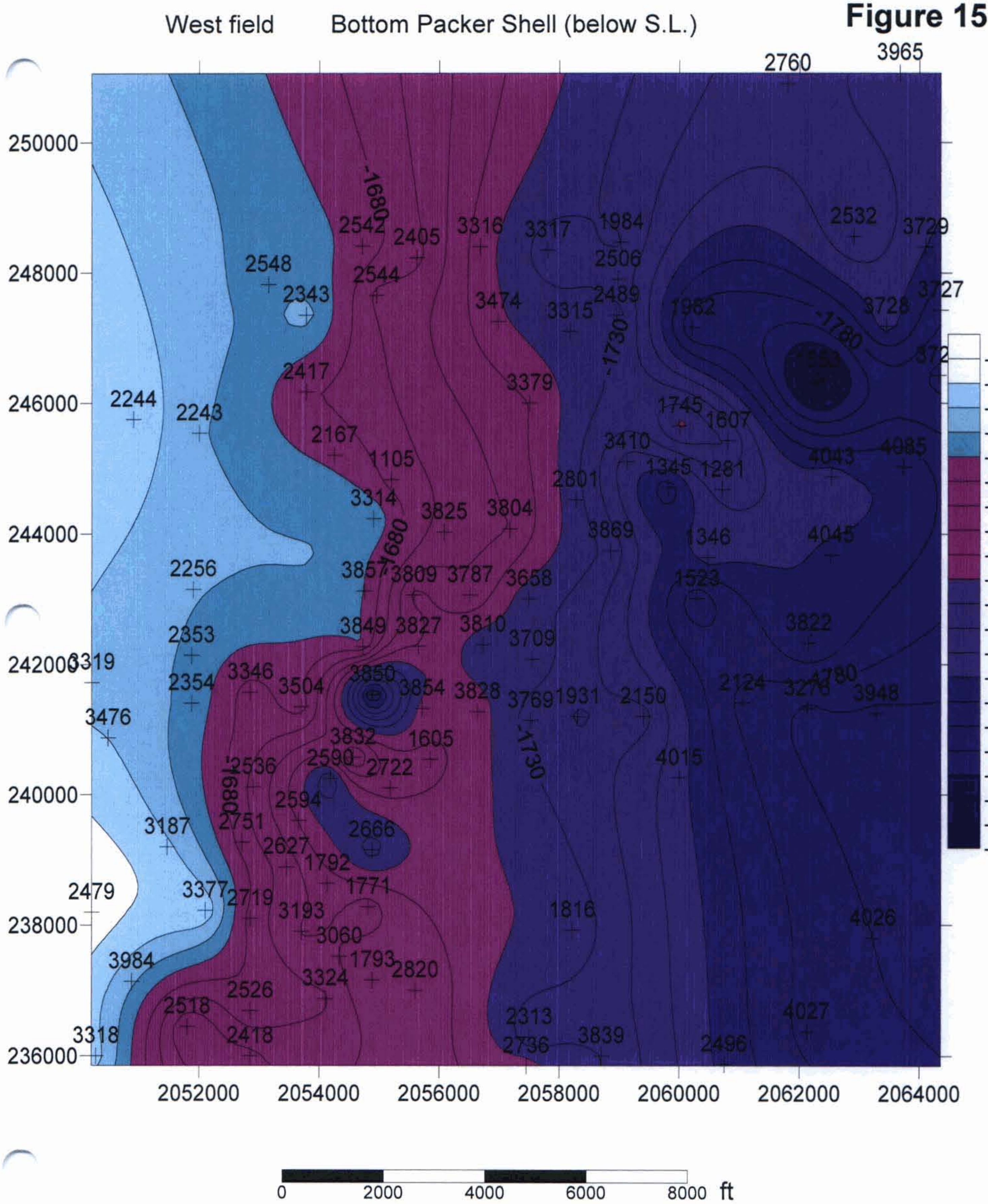
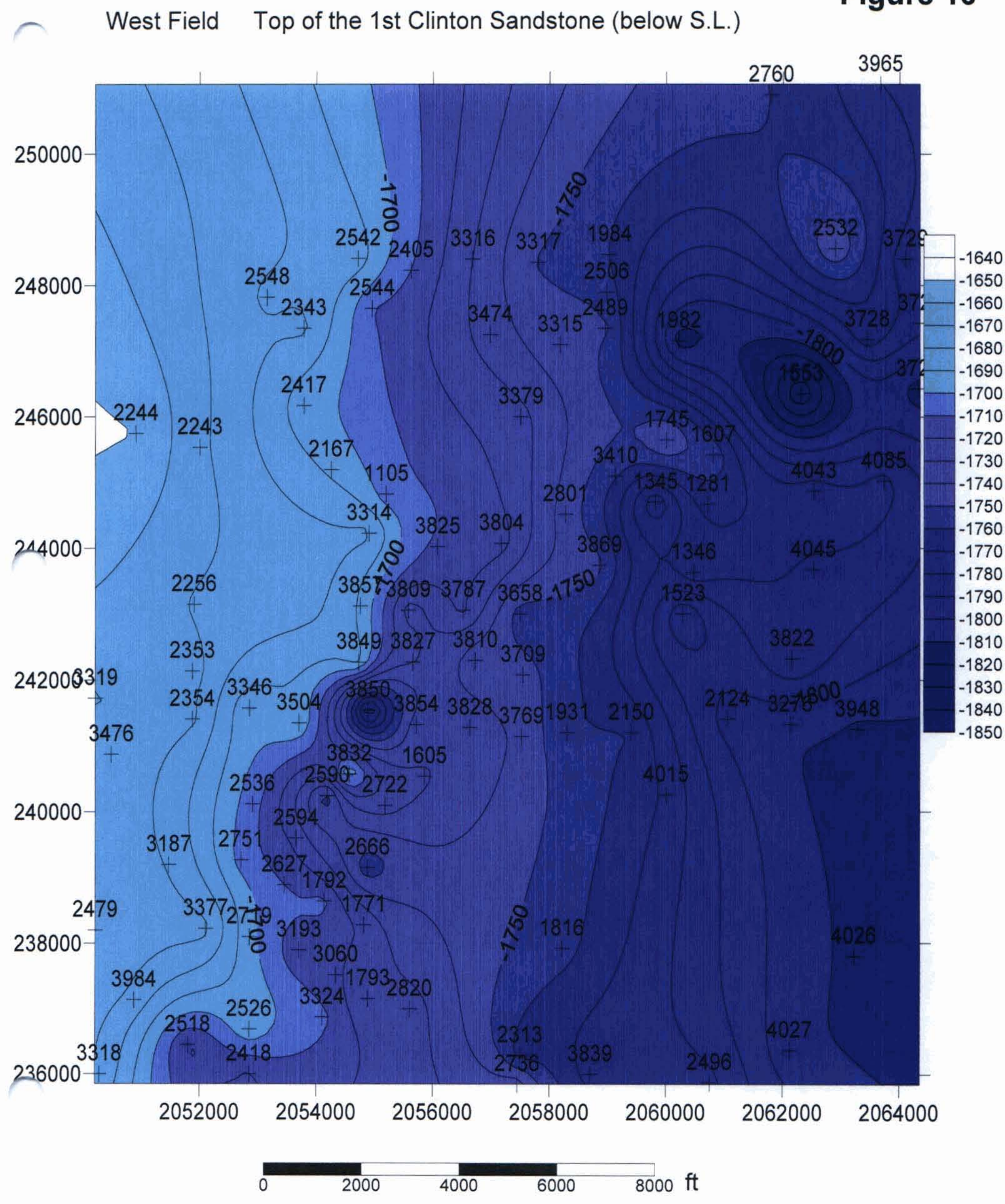

West field
Top Packer Shell (below S.L.)
-1660
-1710
-1760
250000
248000
246000
244000
242000
240000
238000
236000
2052000
2054000
2056000
2058000
2060000
2062000
2064000
-1610
-1620
-1630
-1640
-1650
-1660
-1670
-1680
-1690
-1700
-1710
-1720
-1730
-1740
-1750
-1760
-1770
-1780
-1790
-1800
-1810
0
2000
4000
6000
8000 ft

**Figure 15**

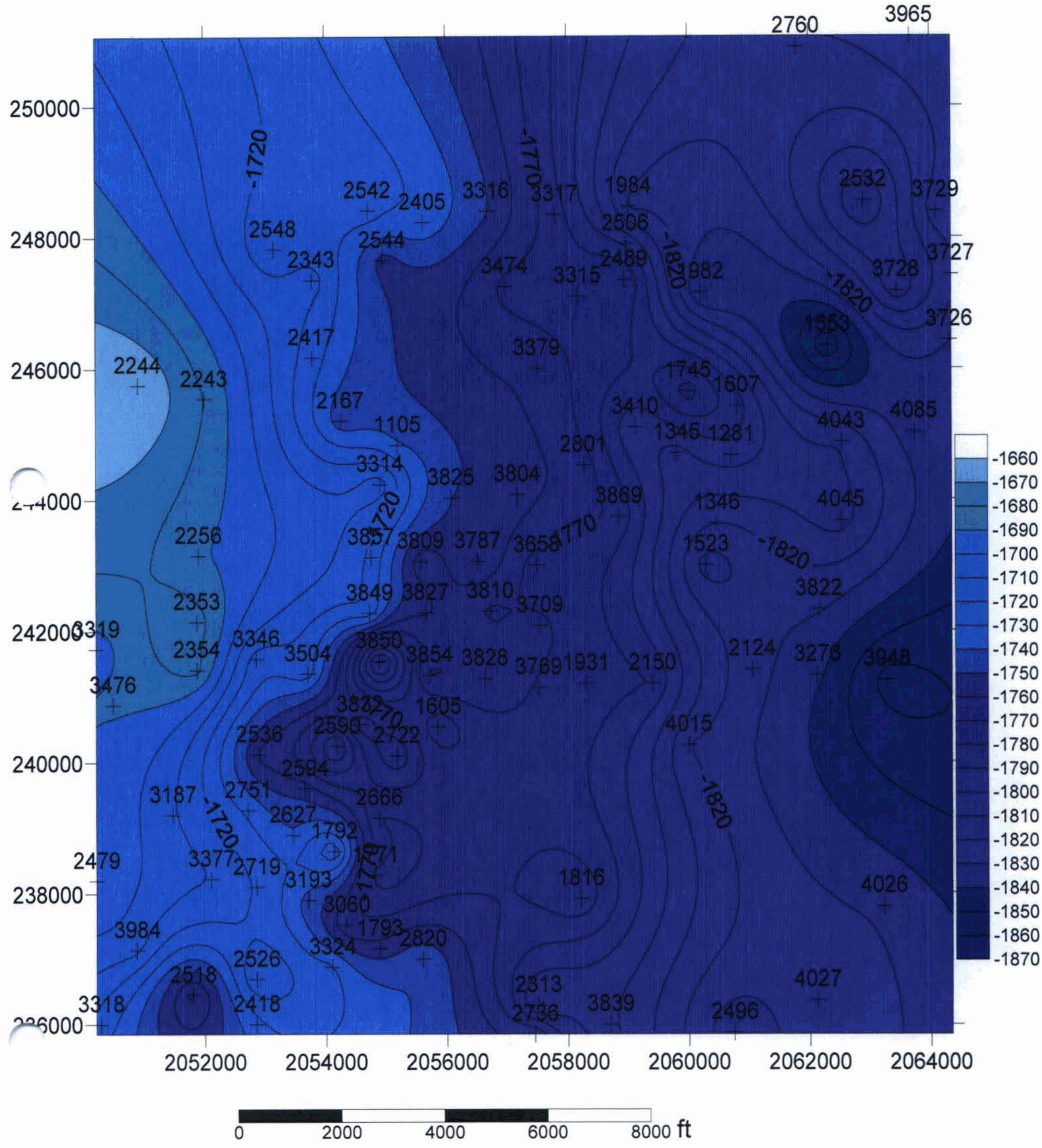

West field
Bottom Packer Shell (below S.L.)
250000
248000
246000
244000
242000
240000
238000
236000
2052000
2054000
2056000
2058000
2060000
2062000
2064000
-1680
-1730
-1780
-1630
-1640
-1650
-1660
-1670
-1680
-1690
-1700
-1710
-1720
-1730
-1740
-1750
-1760
-1770
-1780
-1790
-1800
-1810
-1820
-1830
0
2000
4000
6000
8000
ft

# Figure 16


West Field Top of the 1st Clinton Sandstone (below S.L.)
-1640
-1650
-1660
-1670
-1680
-1690
-1700
-1710
-1720
-1730
-1740
-1750
-1760
-1770
-1780
-1790
-1800
-1810
-1820
-1830
-1840
-1850
250000
248000
246000
244000
242000
240000
238000
236000
2052000
2054000
2056000
2058000
2060000
2062000
2064000
0
2000
4000
6000
8000
ft

# Figure 17

West Field Bottom of the 1st Clinton Sandstone (below S.L.)



Net 1st Clinton Sand   West Field

**Figure 18**

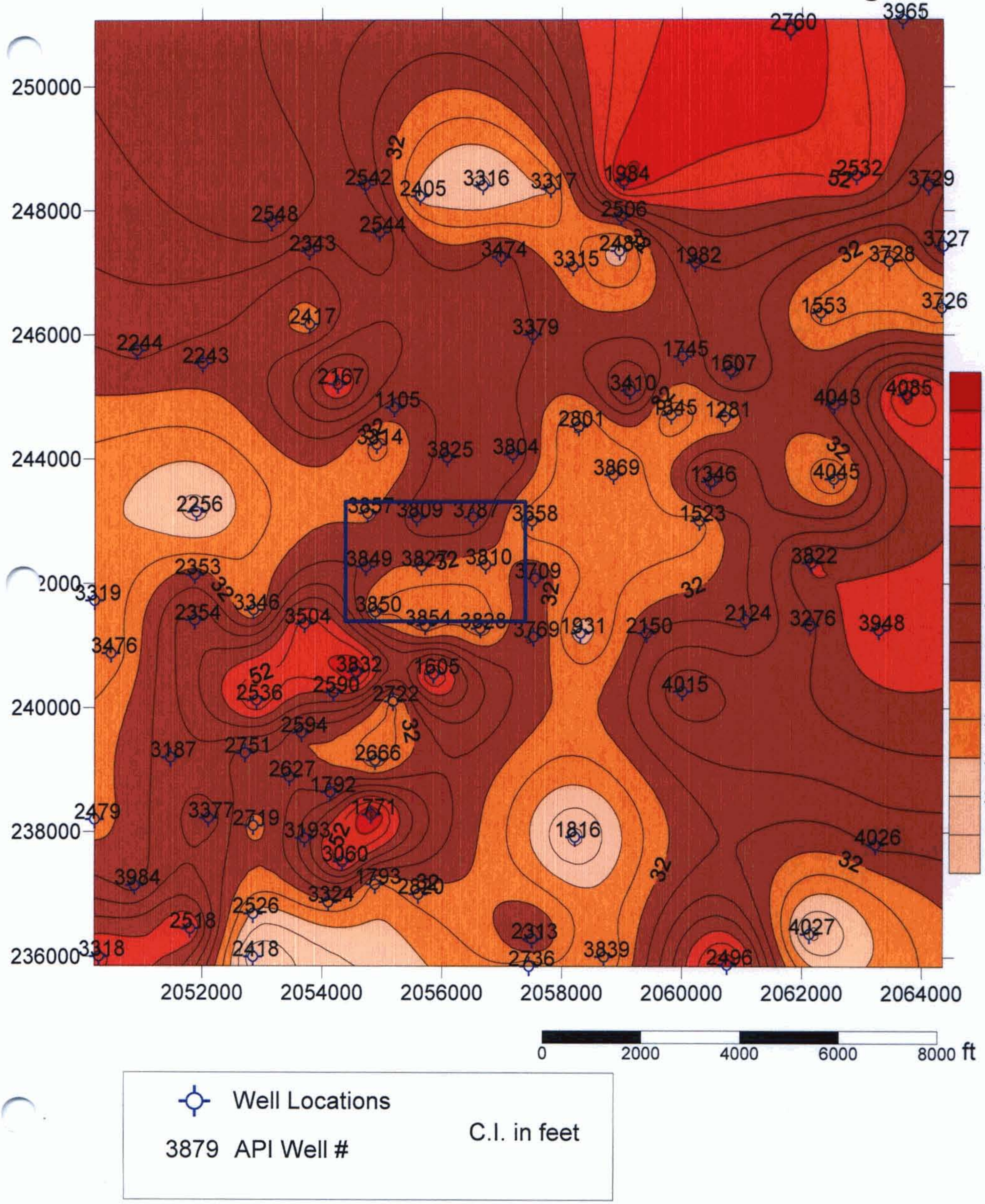
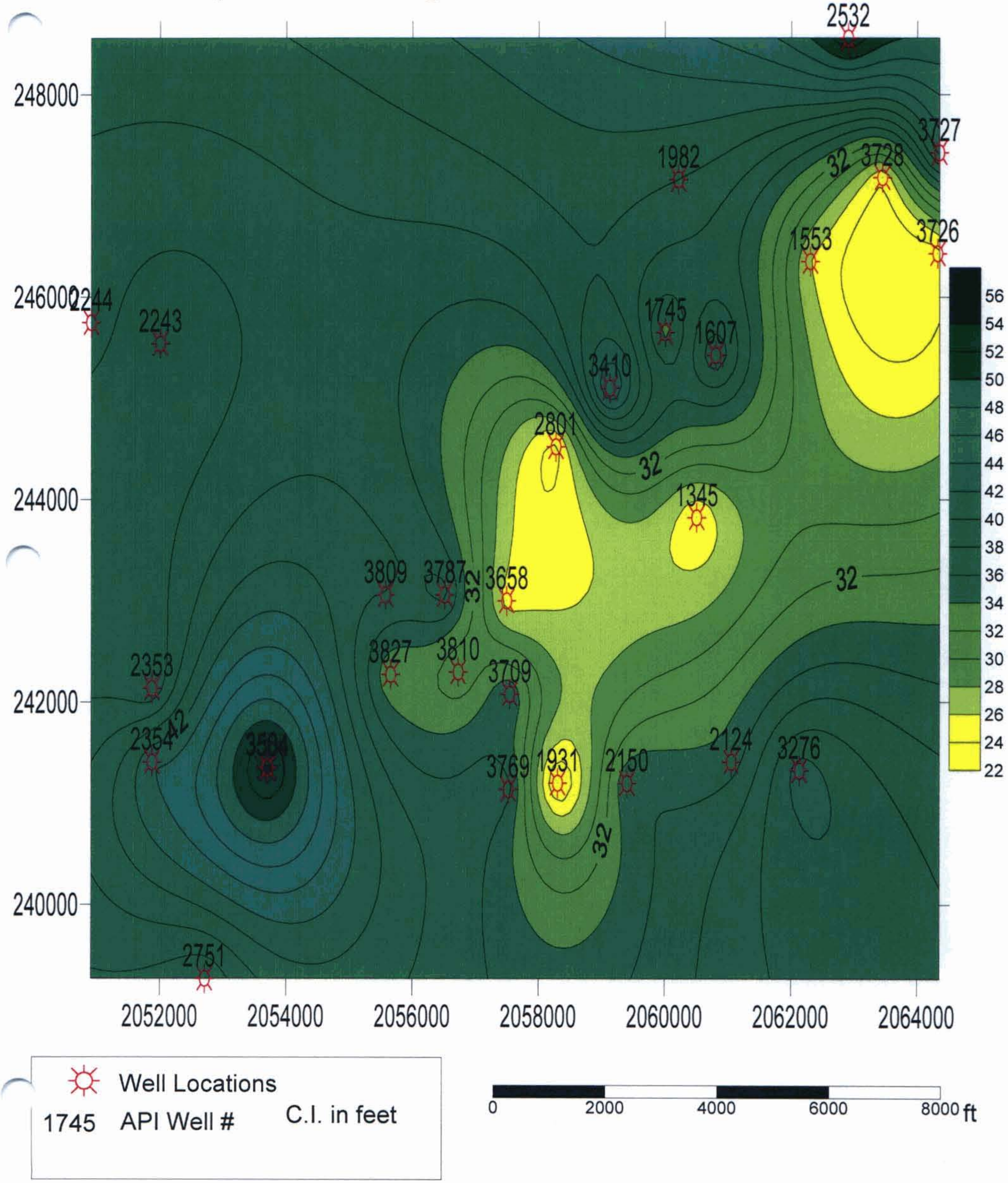


**Figure 19**

Net Clinton Sand ( All Wells contacting the 2nd Clinton Sand in focused area)



# Figure 20

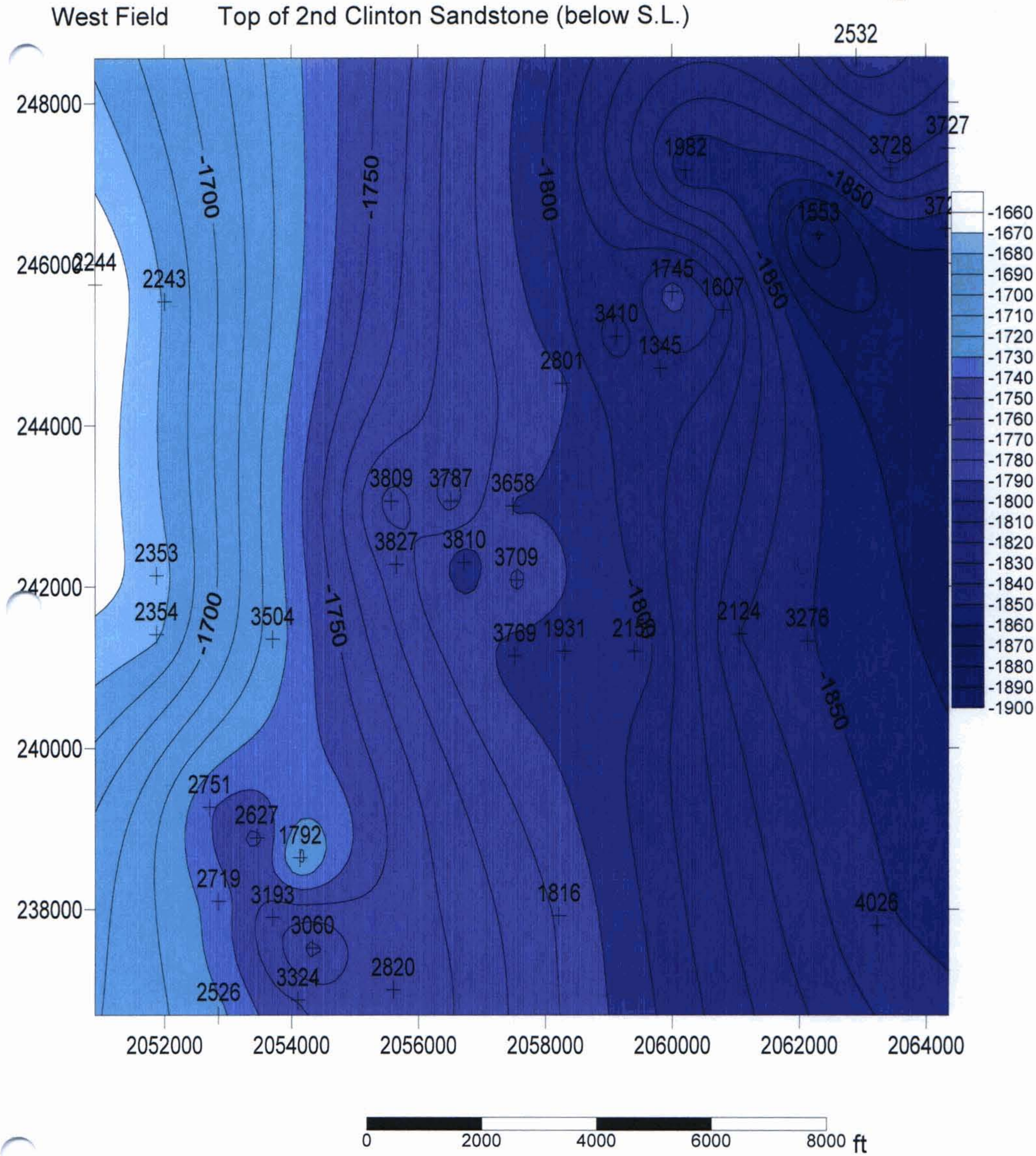
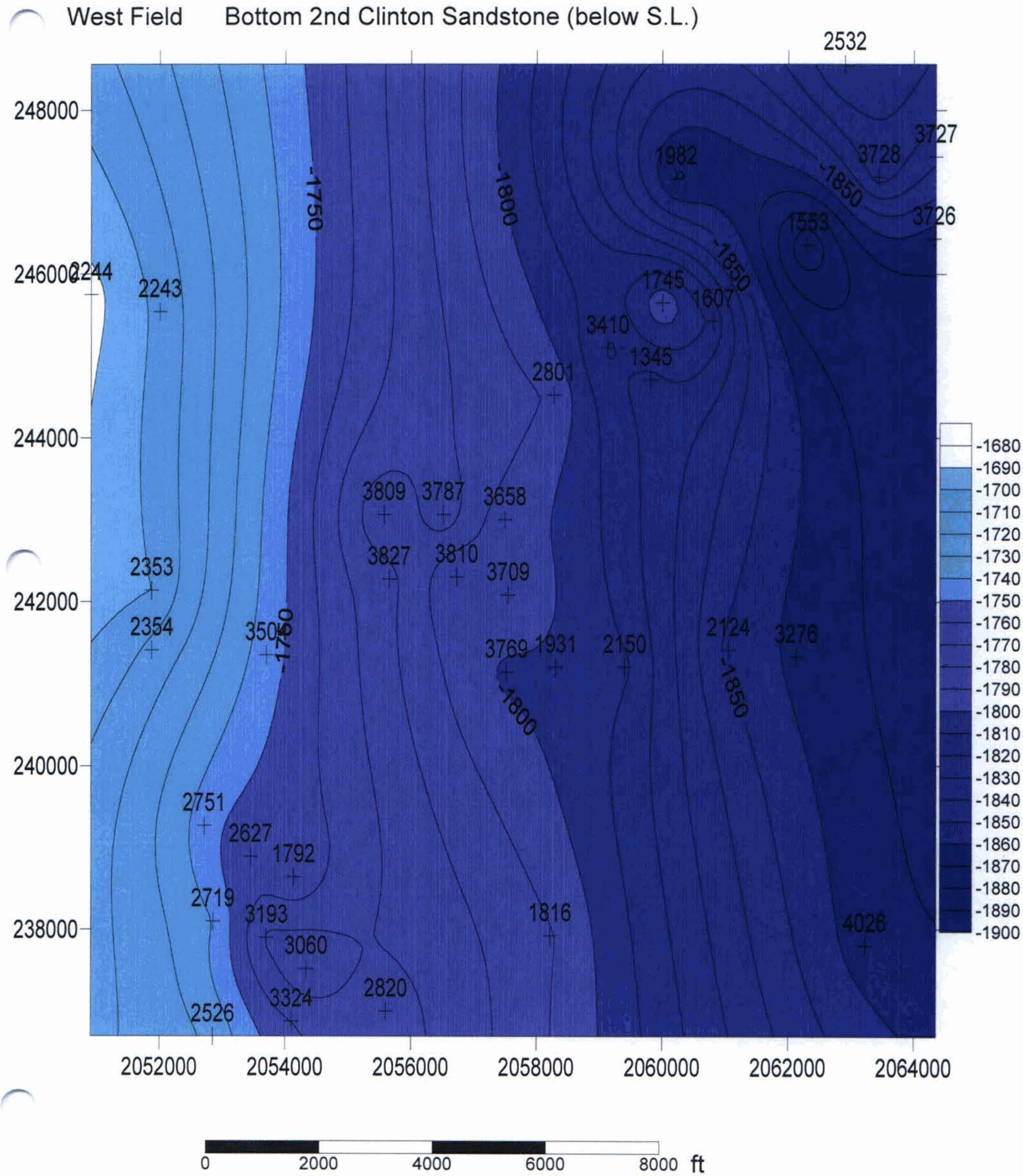

West Field
Top of 2nd Clinton Sandstone (below S.L.)
-1700
-1750
-1800
-1850
2532
3727
3728
1982
1553
1745
1607
3410
1345
2801
2244
2243
3809
3787
3658
3827
3810
3709
2353
2354
3504
3769
1931
2124
3278
2751
2627
1792
2719
3193
1816
4026
3060
3324
2820
2526
248000
246000
244000
242000
240000
238000
2052000
2054000
2056000
2058000
2060000
2062000
2064000
-1660
-1670
-1680
-1690
-1700
-1710
-1720
-1730
-1740
-1750
-1760
-1770
-1780
-1790
-1800
-1810
-1820
-1830
-1840
-1850
-1860
-1870
-1880
-1890
-1900
0
2000
4000
6000
8000 ft

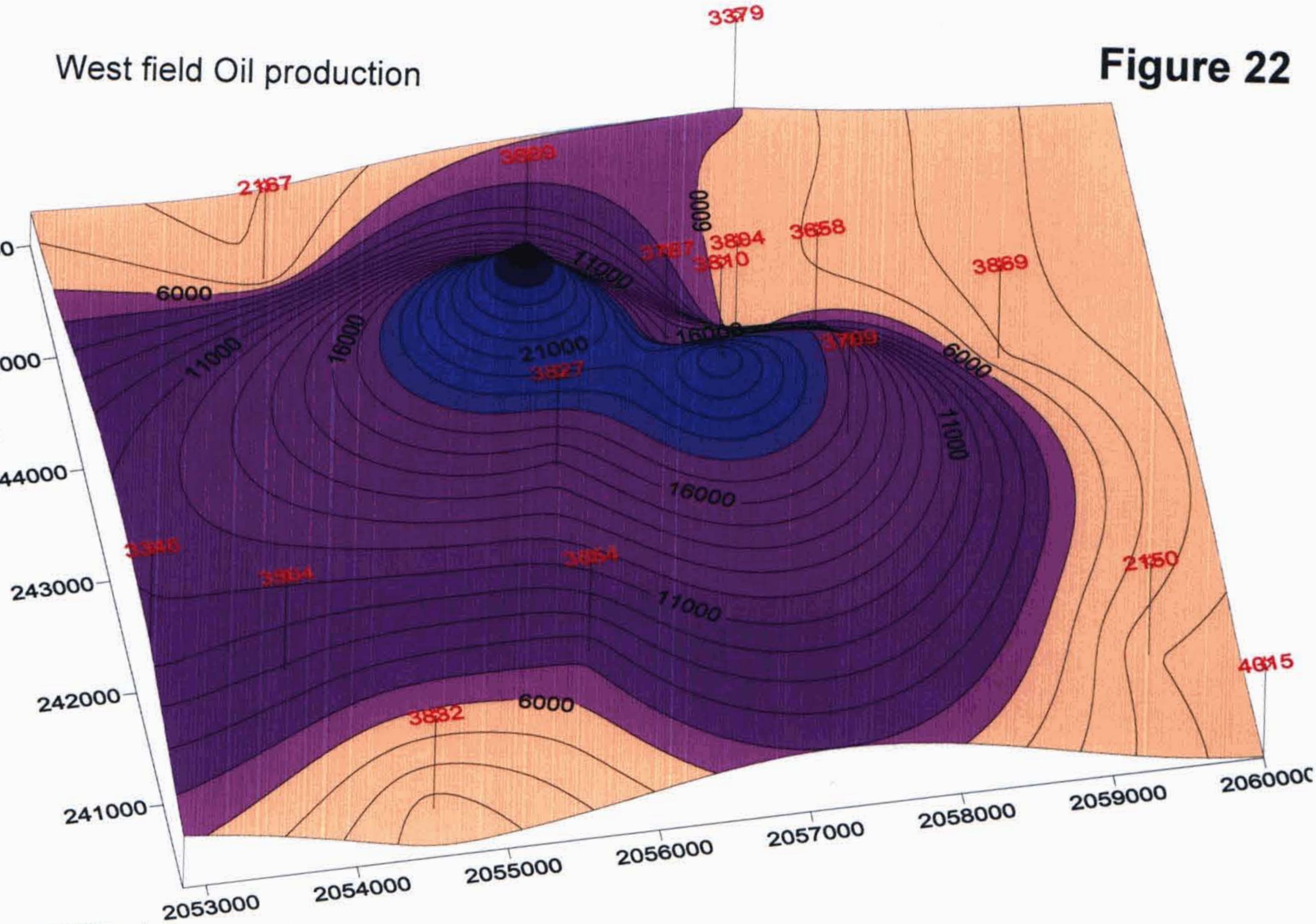
**Figure 21**

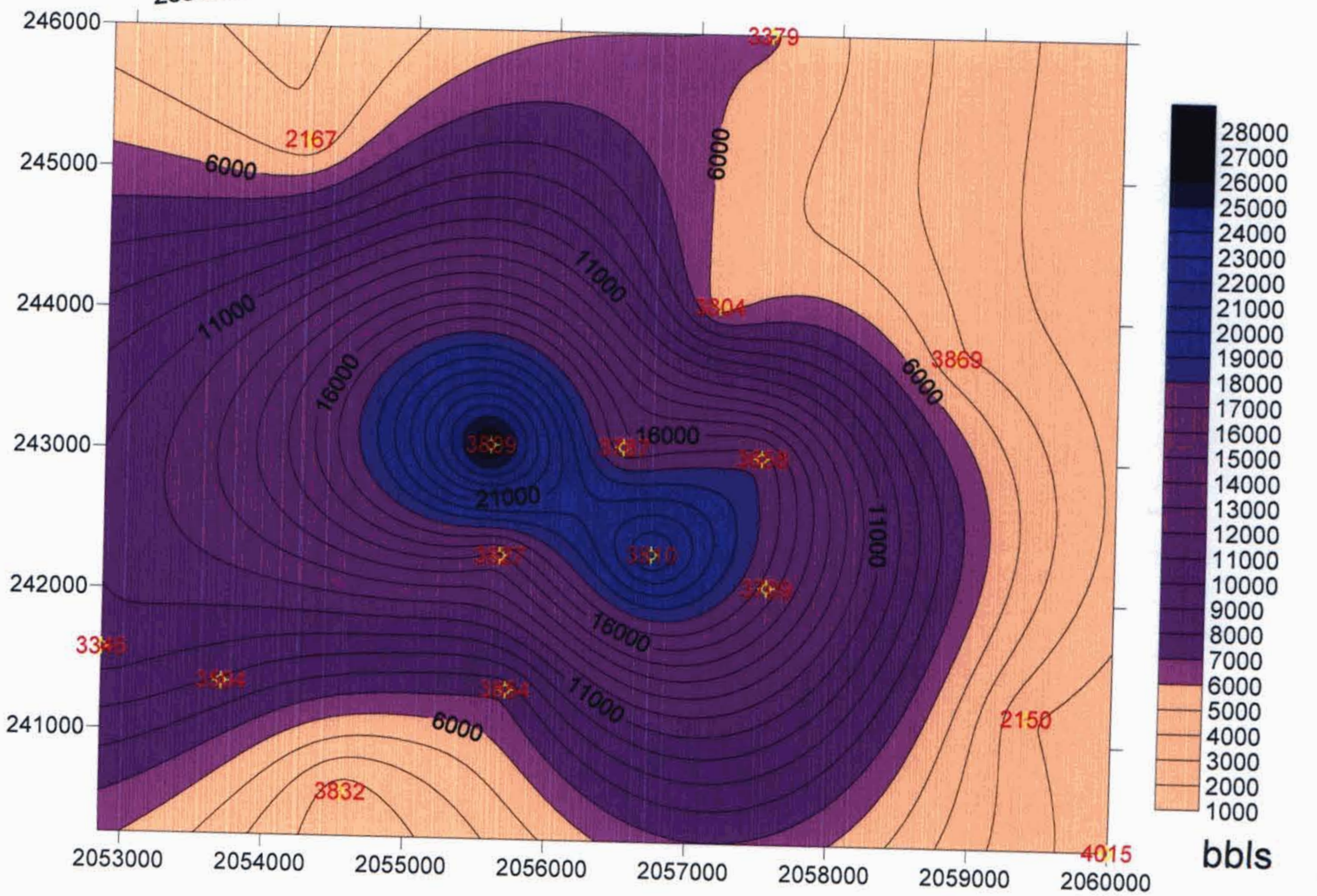


West Field
Bottom 2nd Clinton Sandstone (below S.L.)
248000
246000
244000
242000
240000
238000
2052000
2054000
2056000
2058000
2060000
2062000
2064000
-1750
-1800
-1850
-1680
-1690
-1700
-1710
-1720
-1730
-1740
-1750
-1760
-1770
-1780
-1790
-1800
-1810
-1820
-1830
-1840
-1850
-1860
-1870
-1880
-1890
-1900
0
2000
4000
6000
8000
ft

West field Oil production

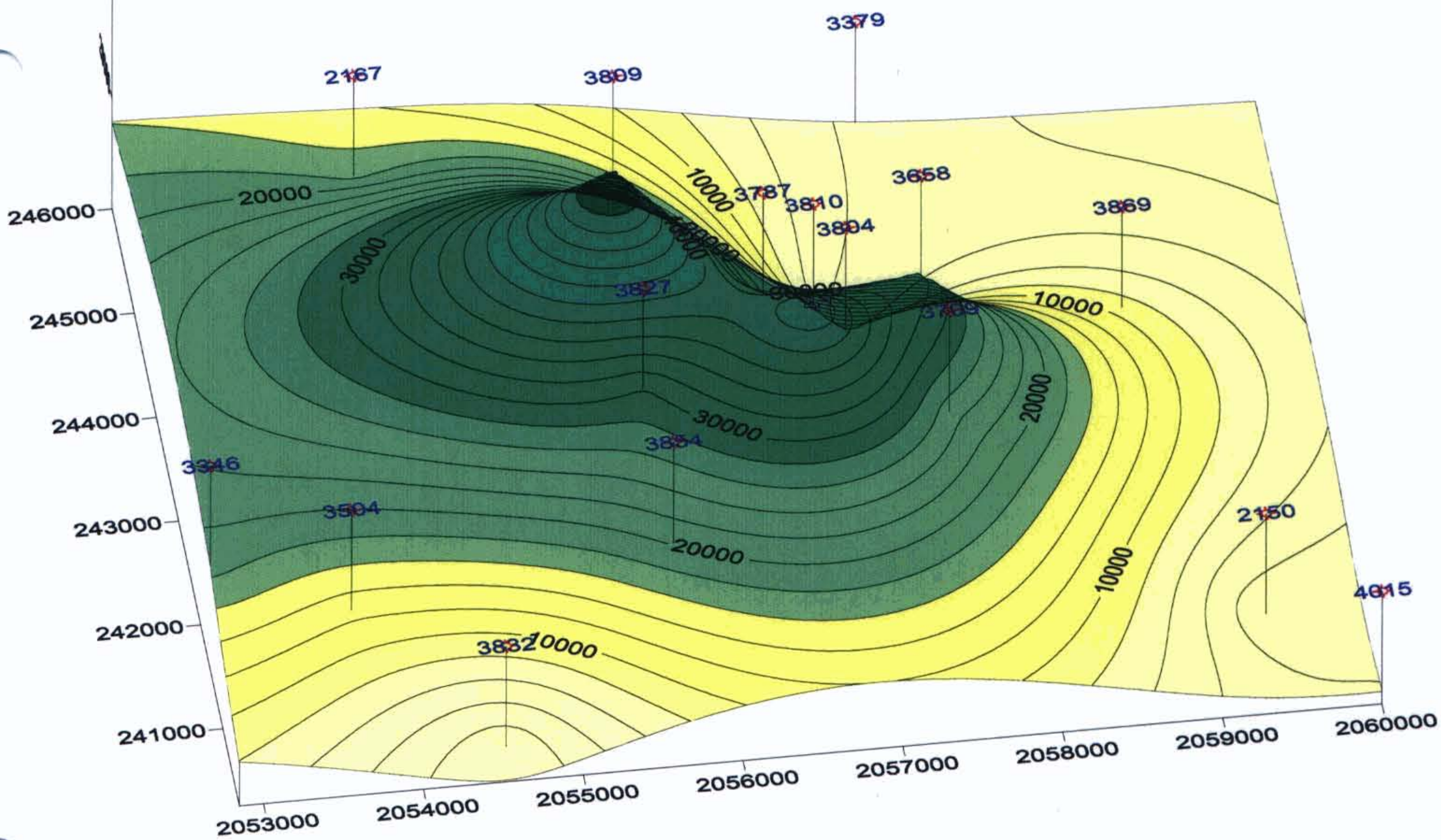
**Figure 22**

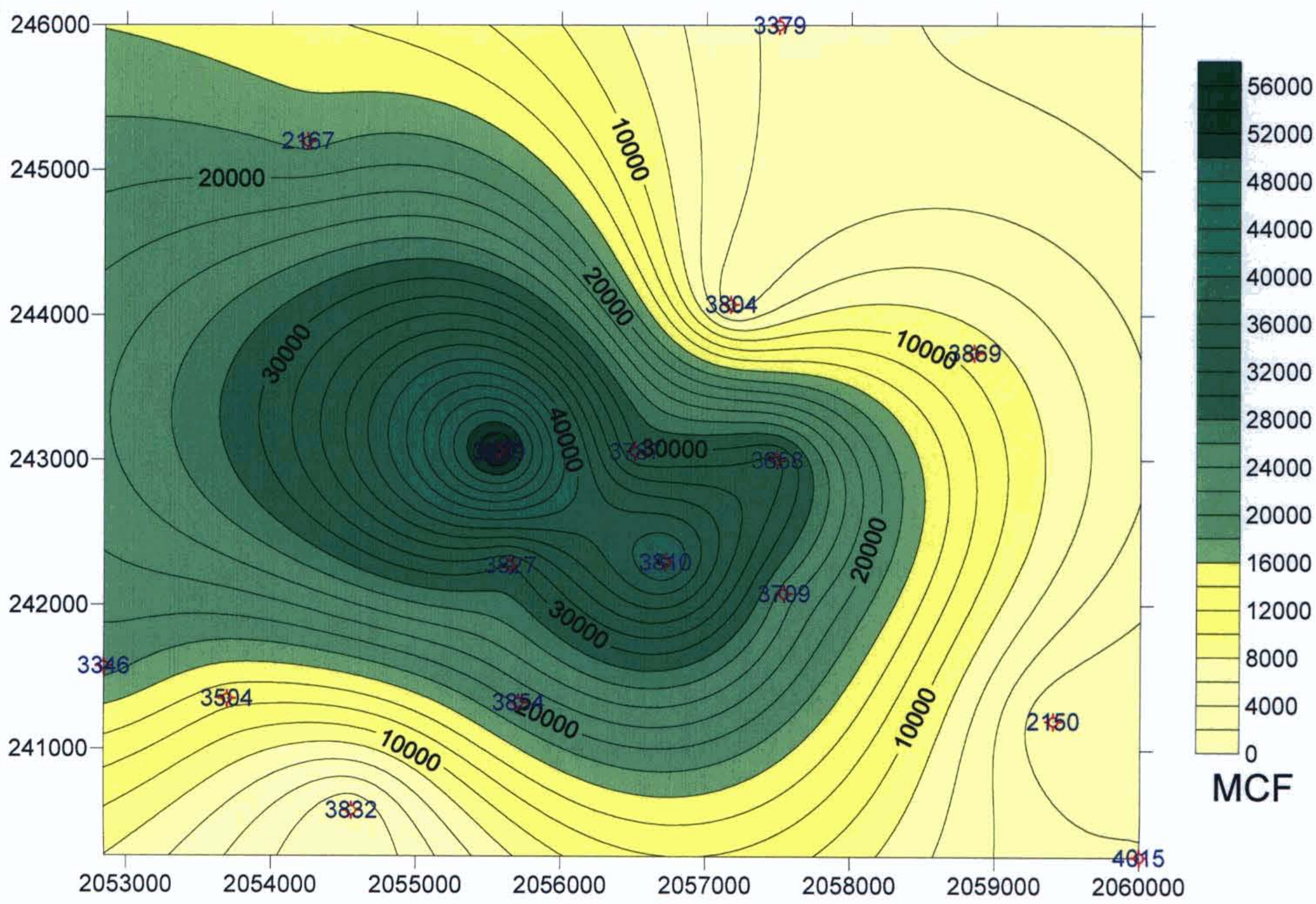


West field gas production

**Figure 23**



# Figure 24

West field Cross sections

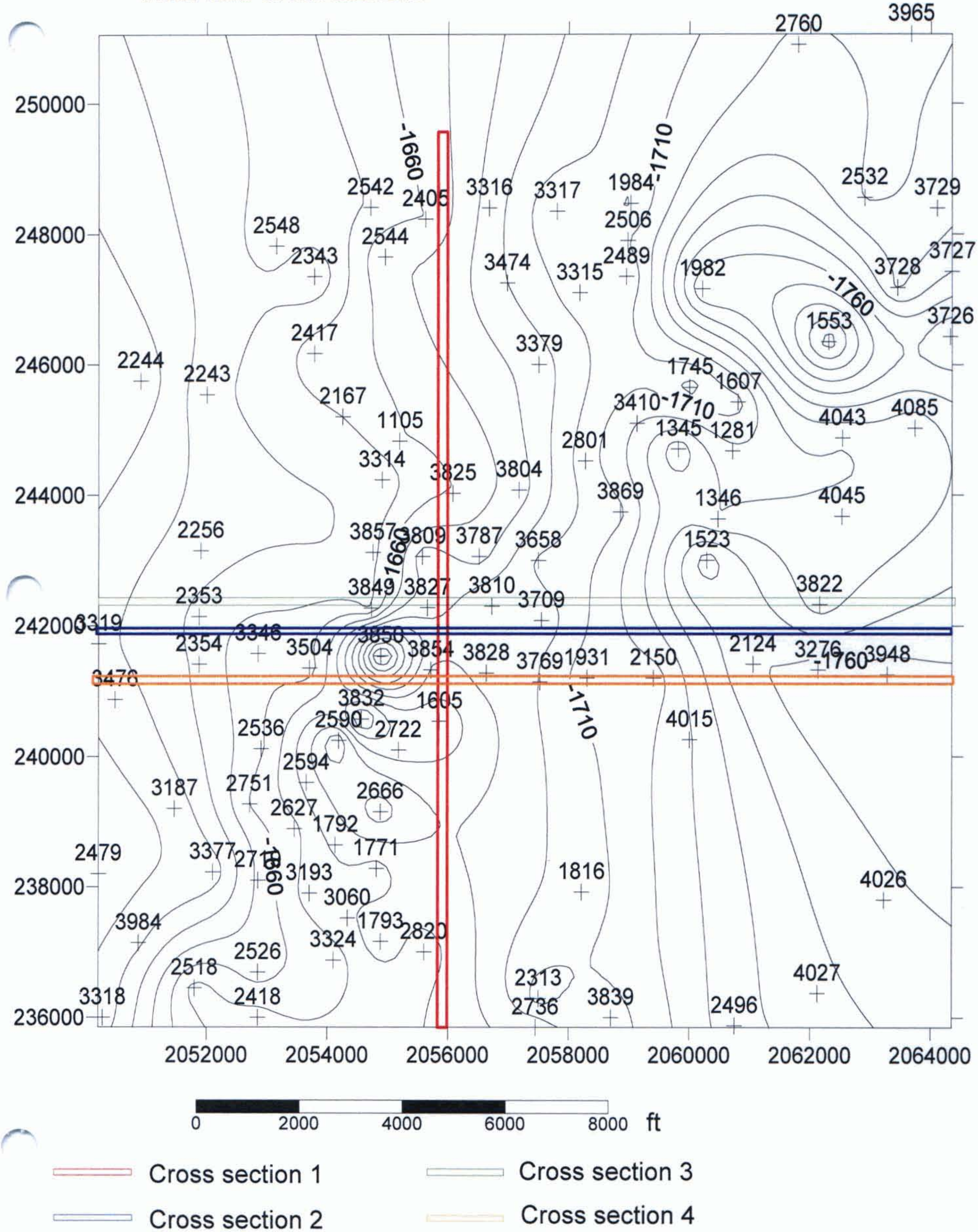


**Figure 25**

Cross section 1 West field line @ 2056000

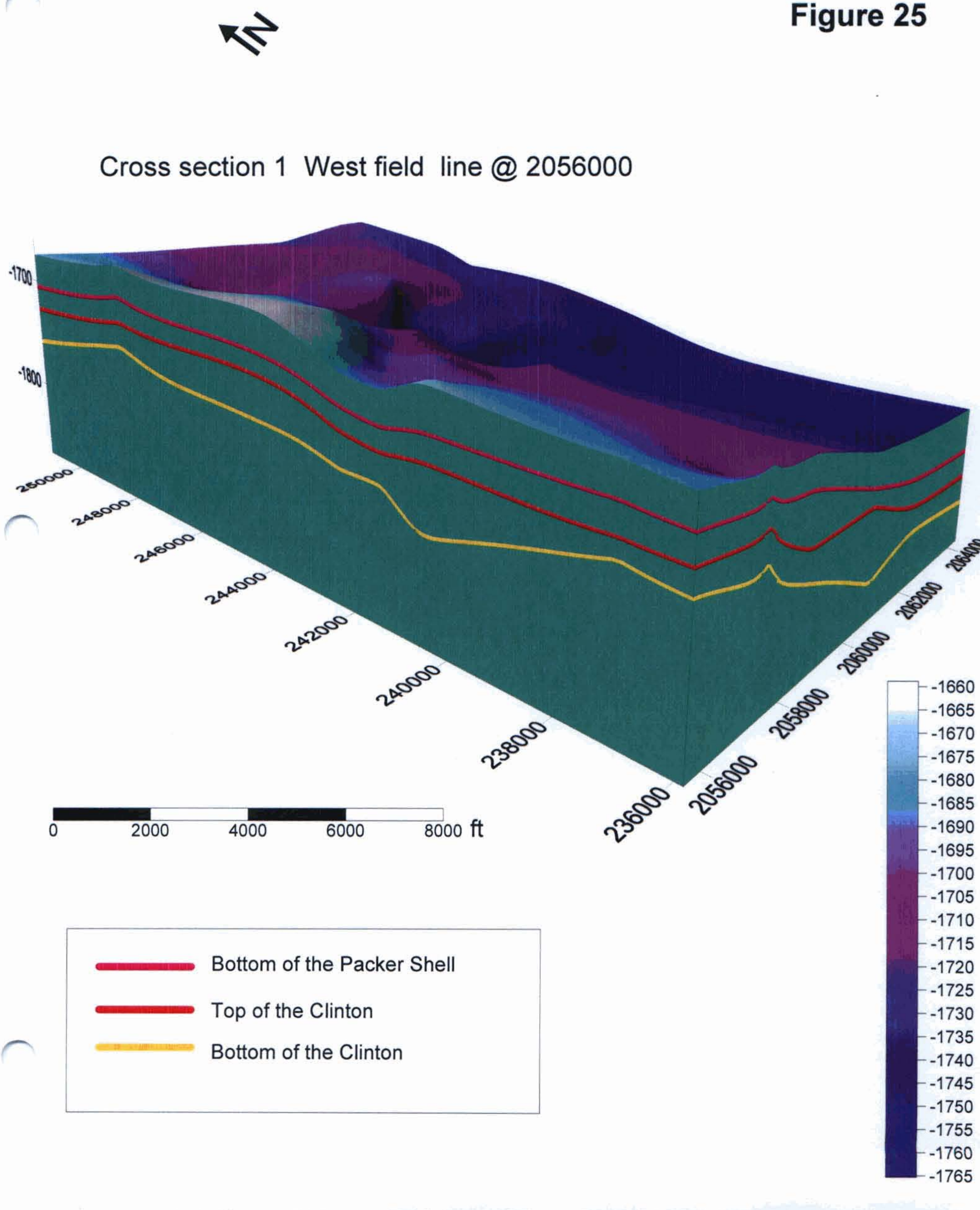
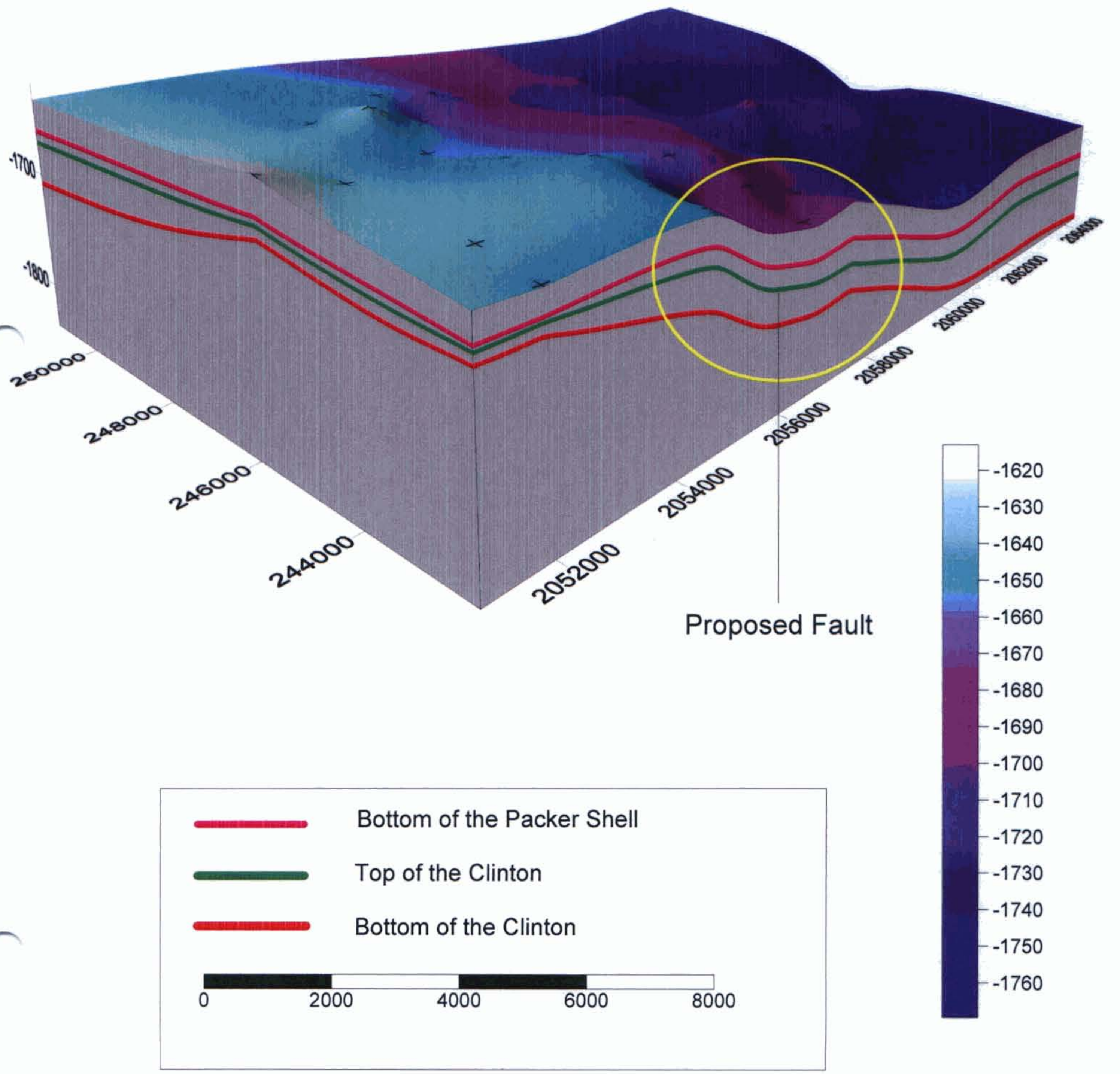


**Figure 26**

Cross Section 2 West Field line @ 242000



Cross section 3 West field line at 242000

**Figure 27**

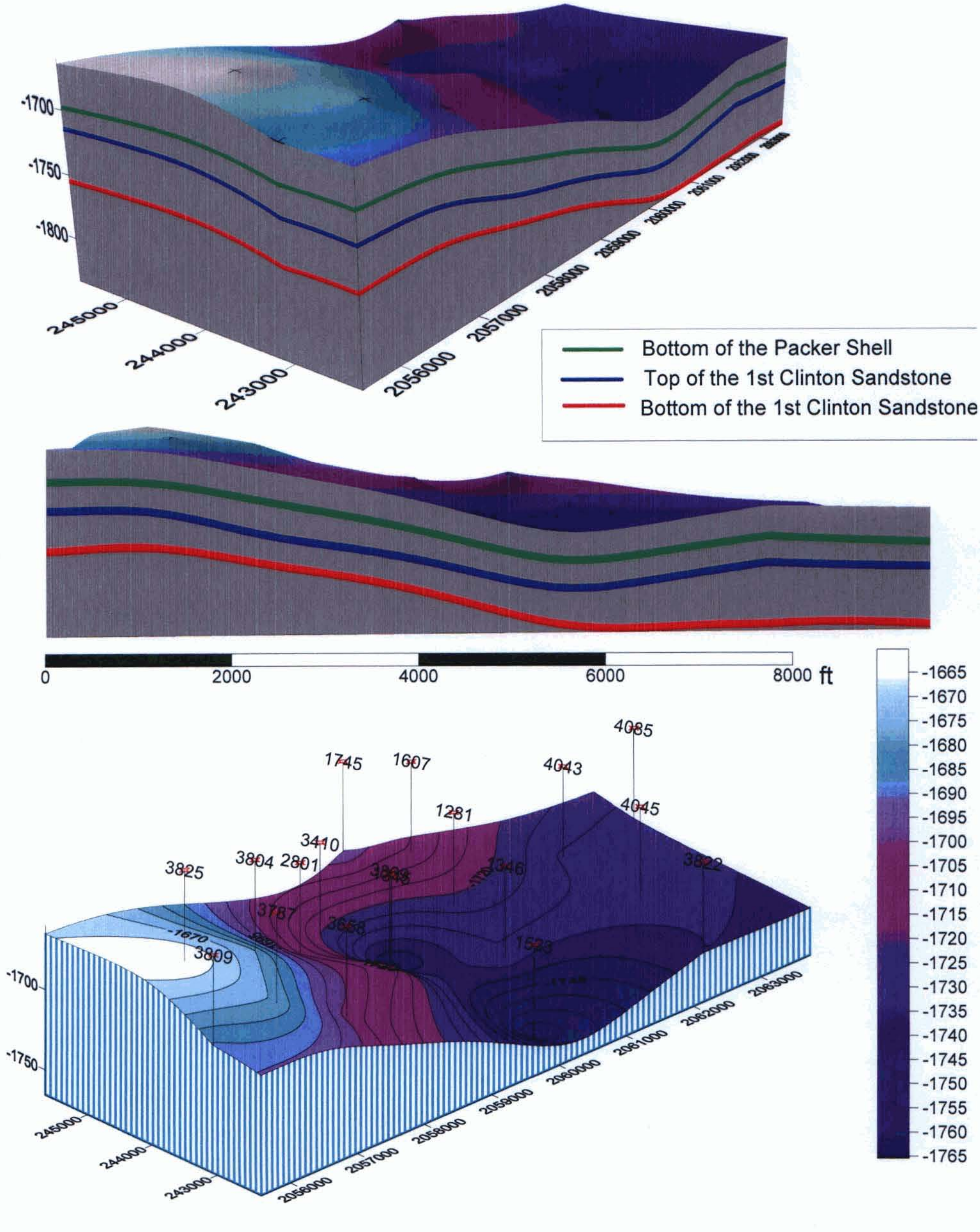


**Figure 28**

# Cross section 4 (West Field)

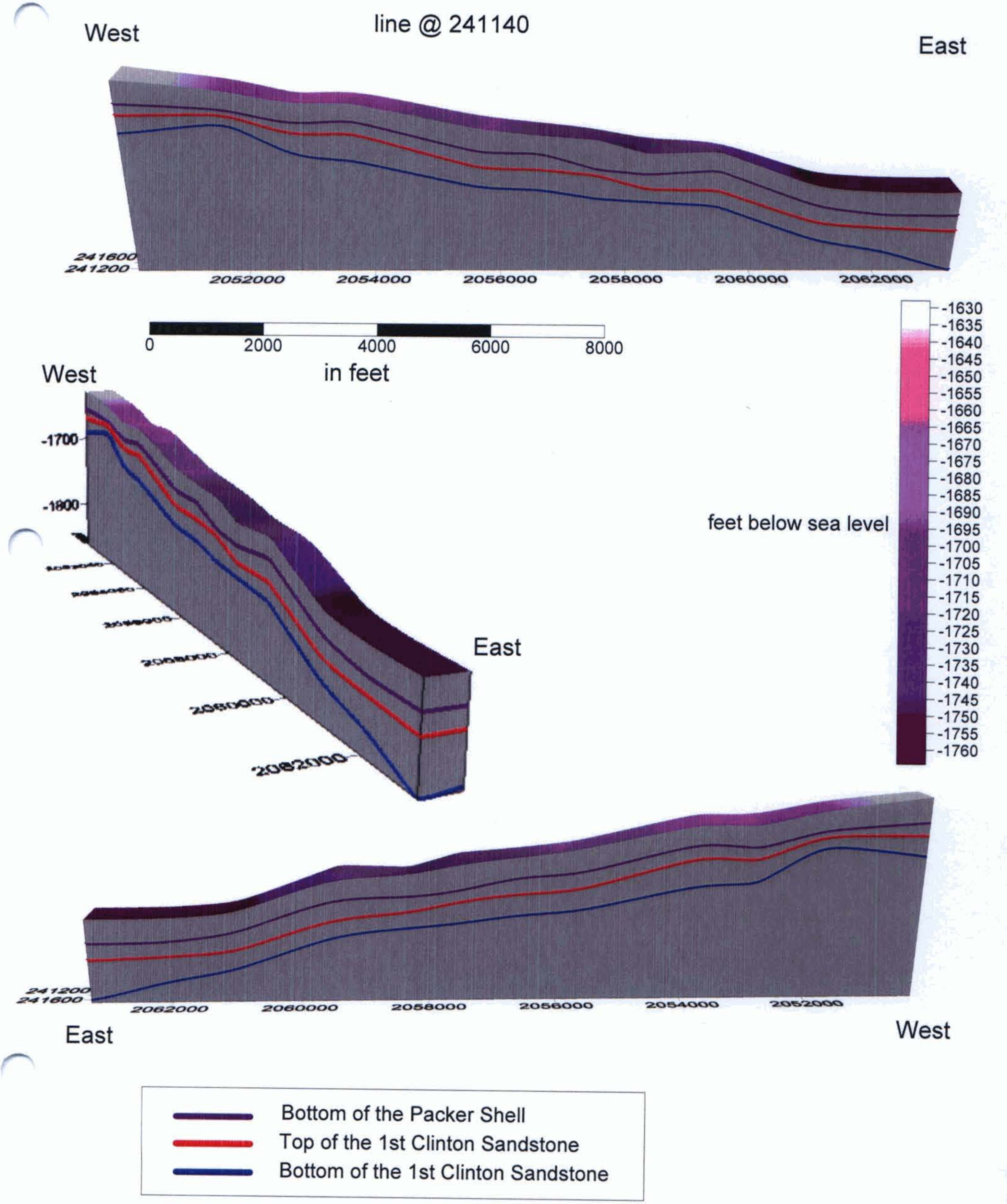
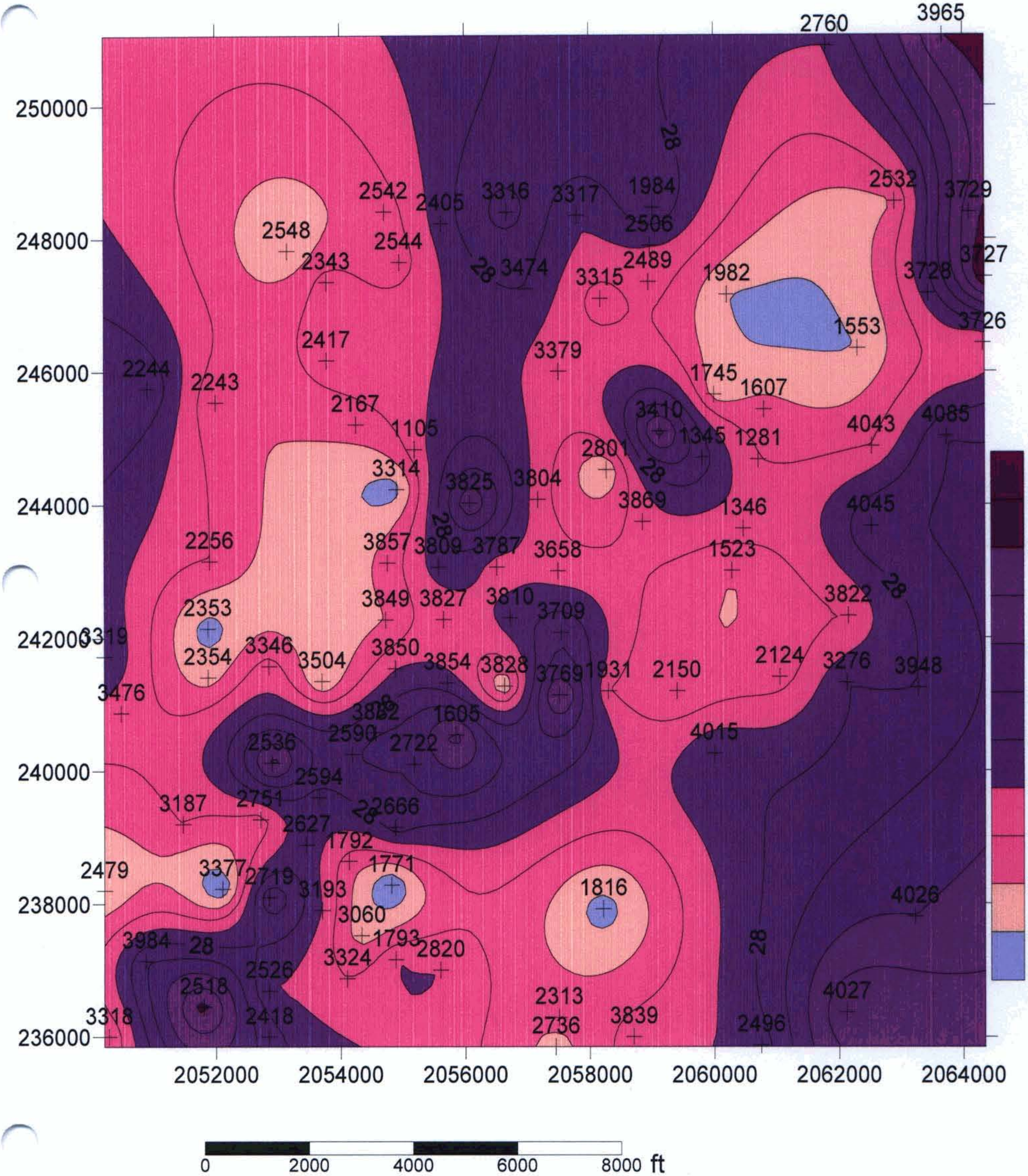


**Figure 29**

West Field    Net Thickness of the Packer Shell



# Figure 30

East Field Net thickness of the 1st Clinton Sand

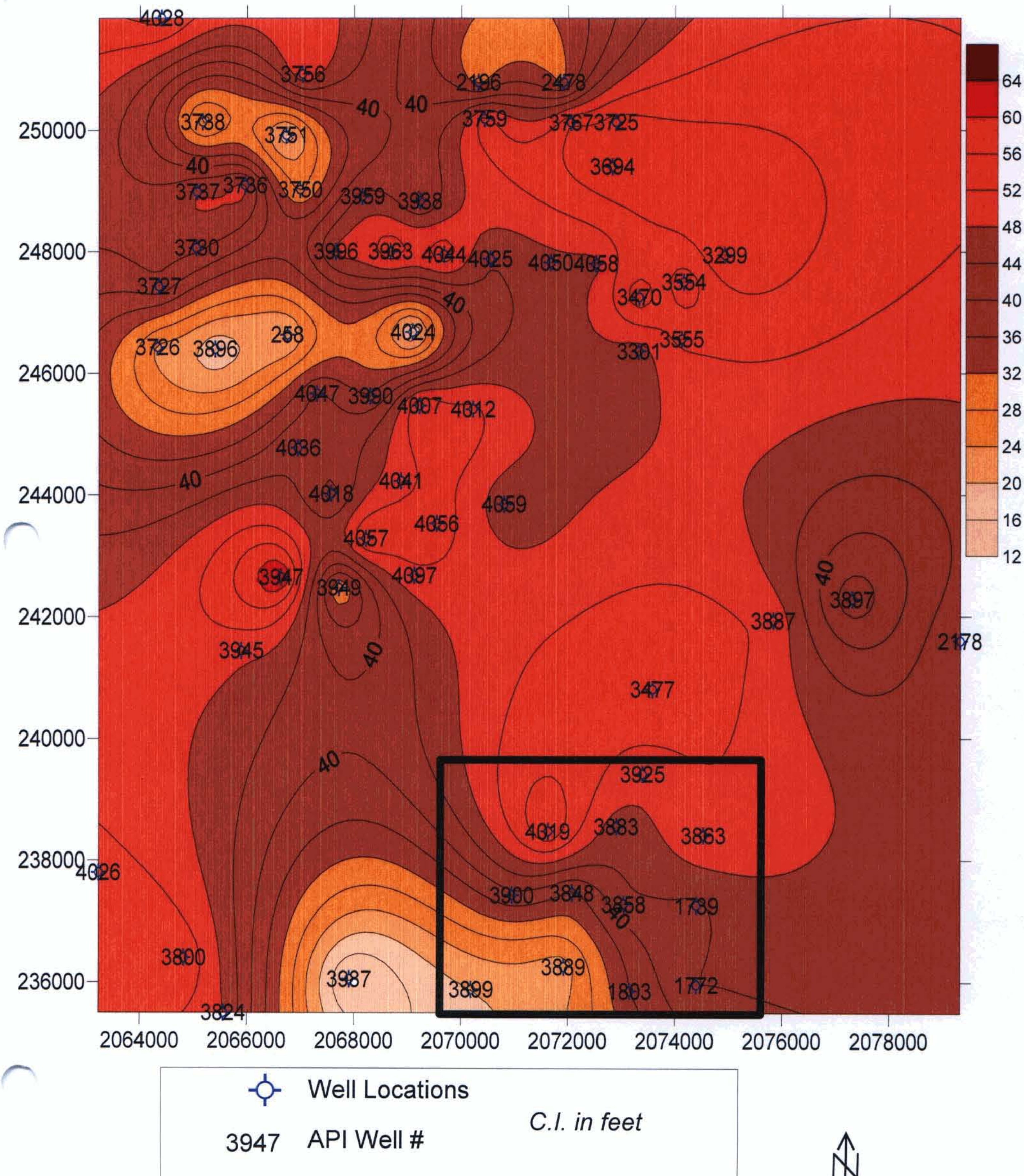


**Figure 31**

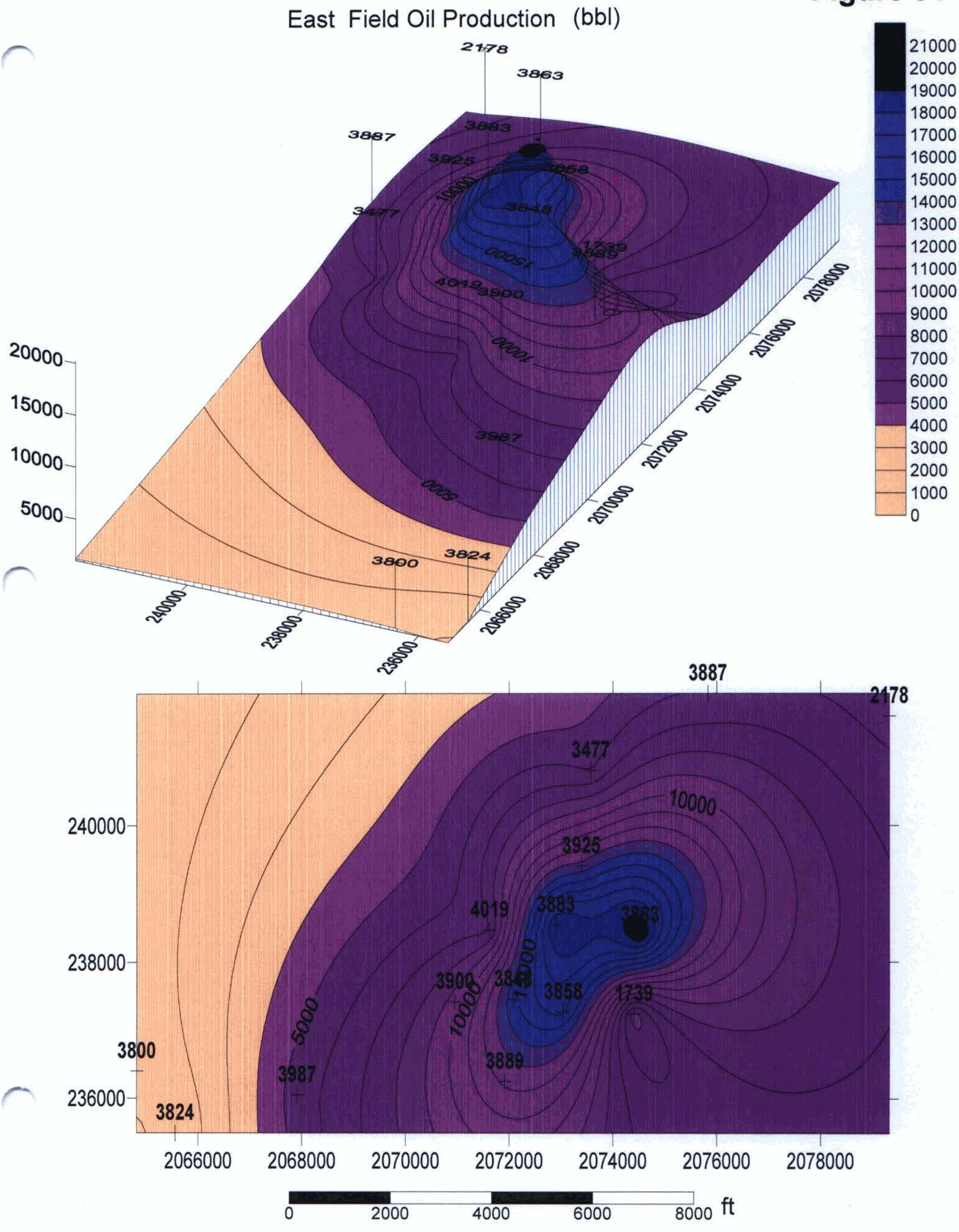
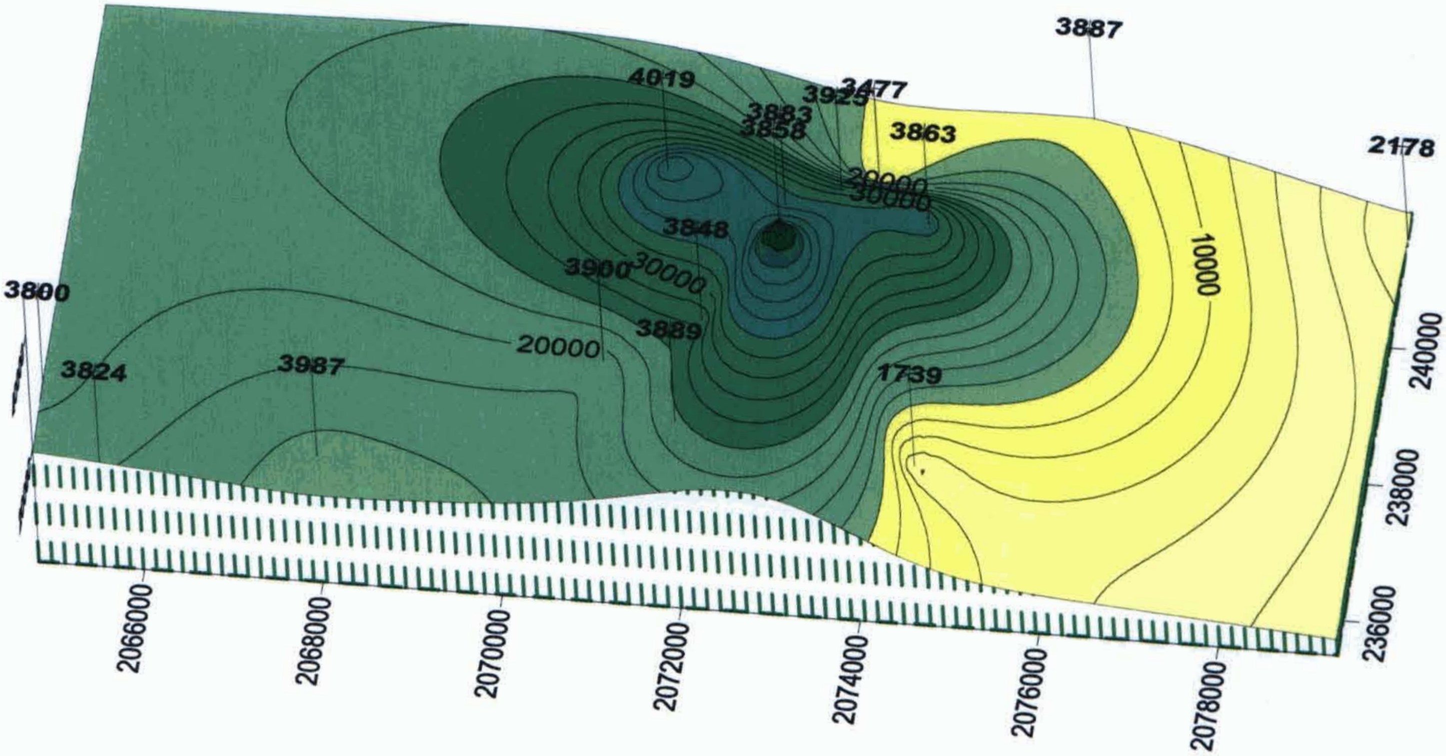

East Field Oil Production (bbl)
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
2178
3863
3887
3883
3925
3858
3848
3477
1739
3889
15000
4019
3900
10000
3987
5000
3800
3824
20000
15000
10000
5000
240000
238000
236000
2066000
2068000
2070000
2072000
2074000
2076000
2078000
0
2000
4000
6000
8000
ft

**Figure 32**

East field Gas Production (MCF)



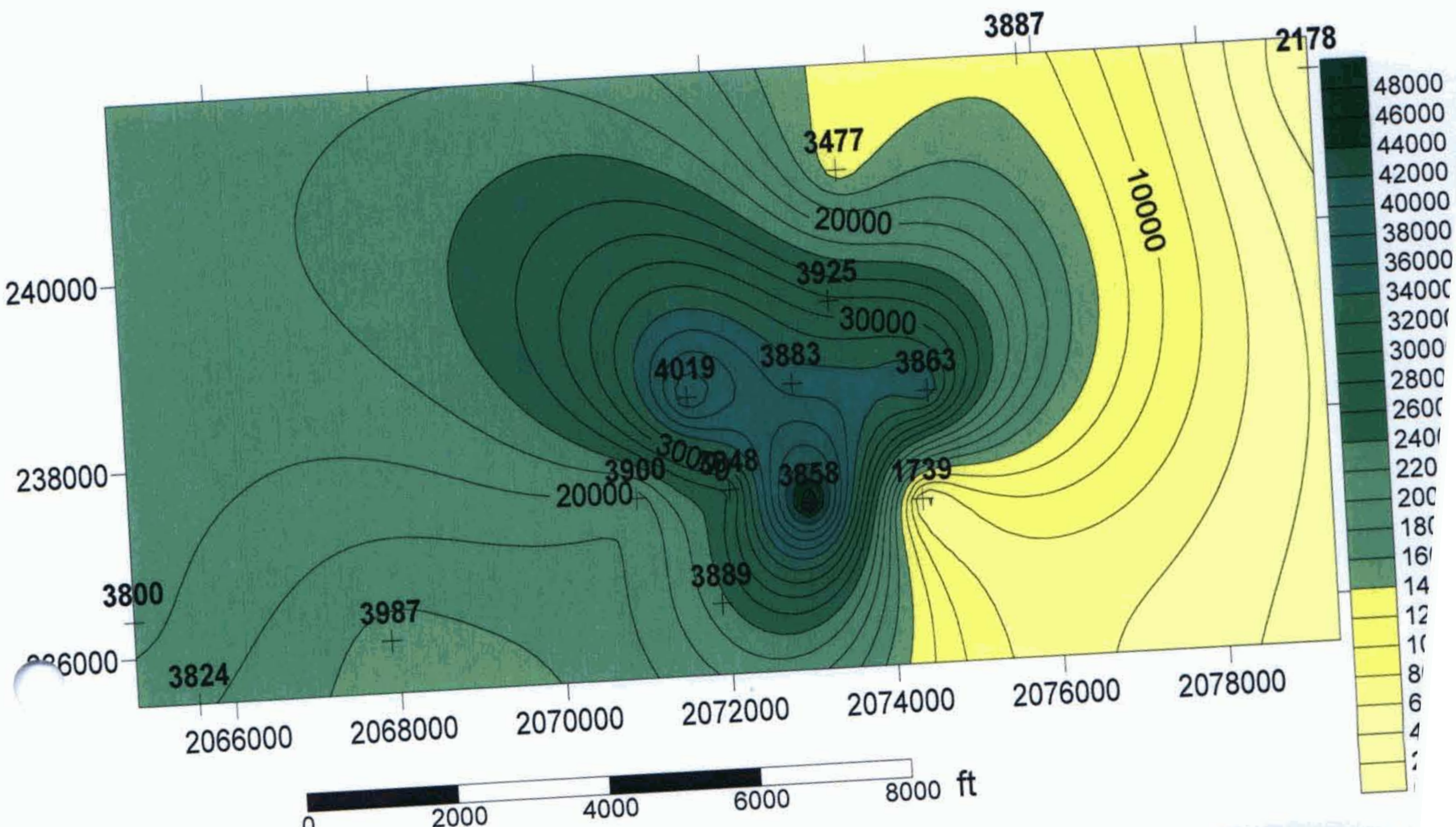
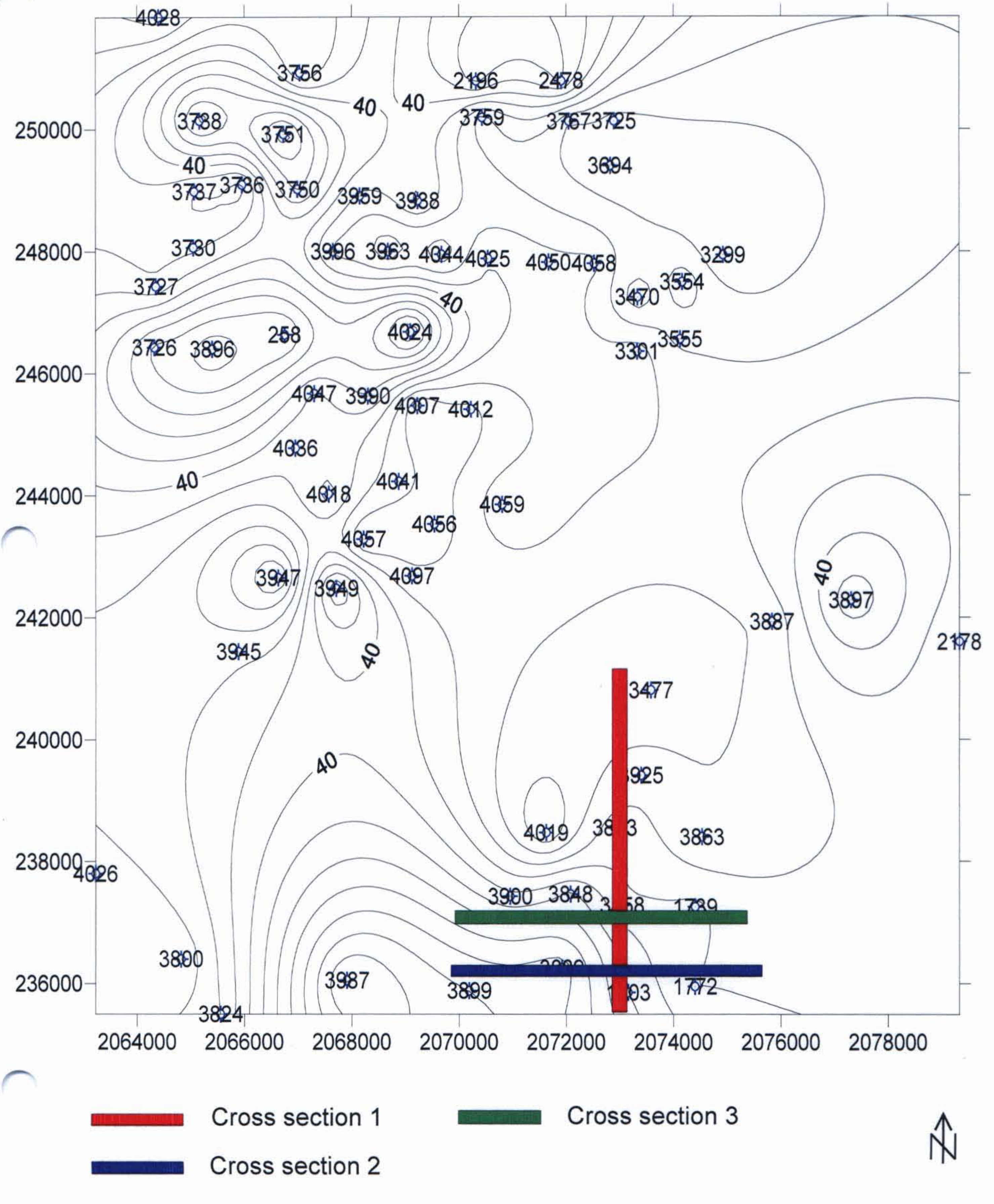



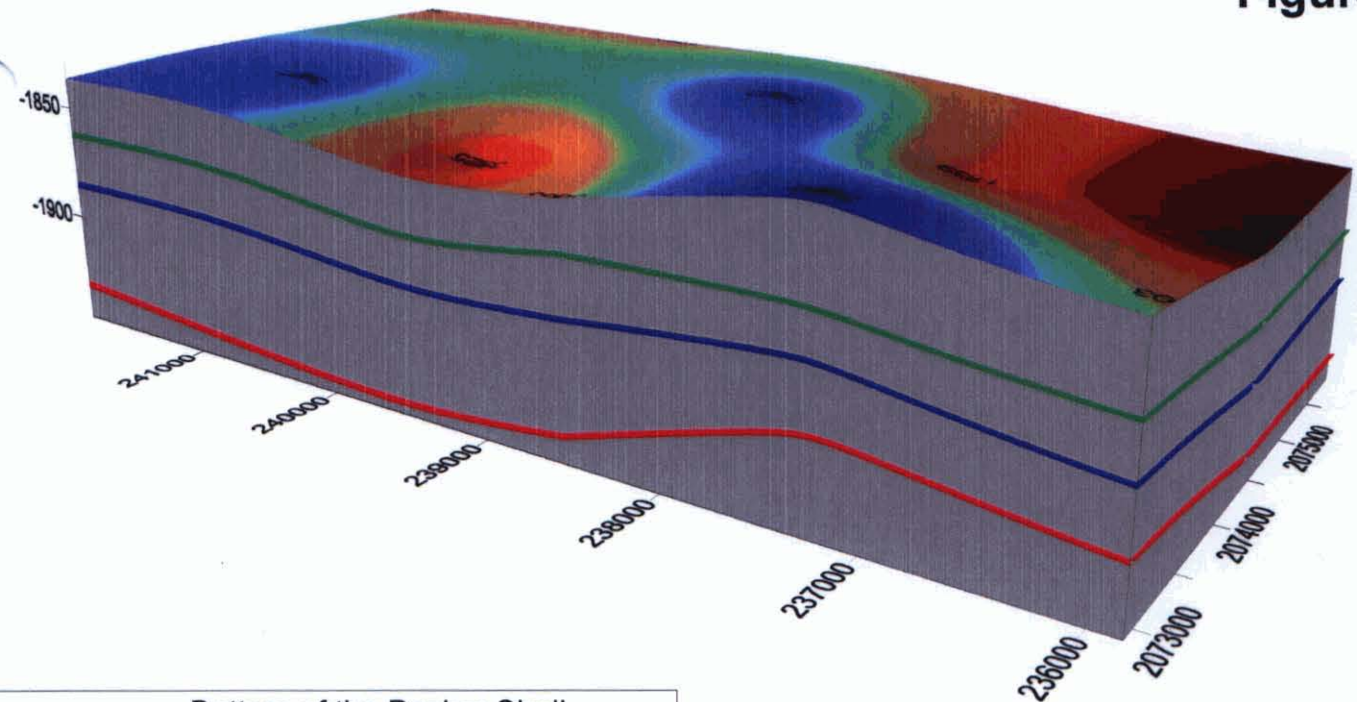
Figure 33

East Field Net thickness of the 1st Clinton Sand



Cross section 1 East Field line at 2073000

**Figure 34**

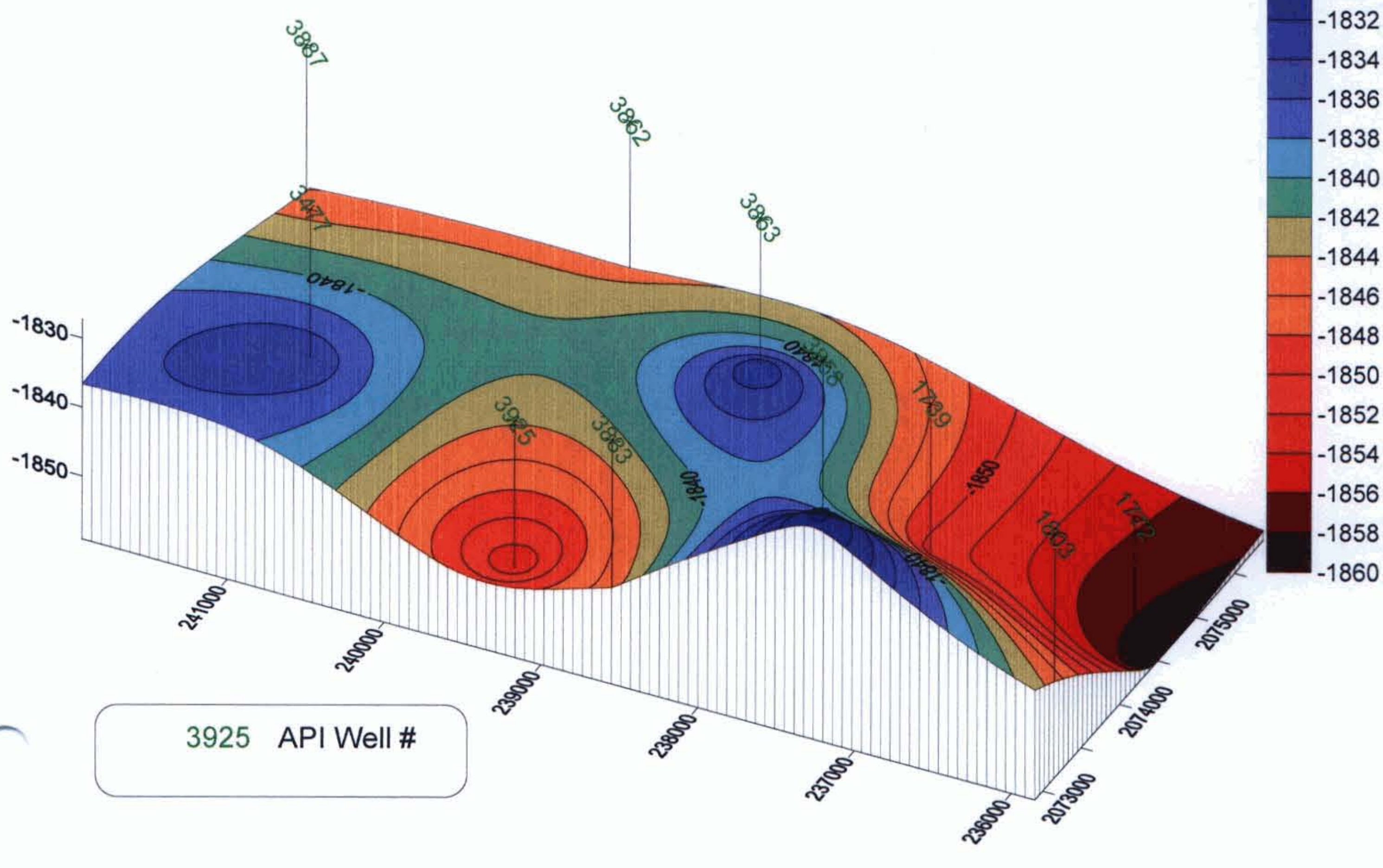



Bottom of the Packer Shell

Top of the Clinton 1 Sandstone

Bottom of the Clinton 1 Sandstone

0 500 1000 1500 2000 ft




3925 API Well #

# Figure 35

Cross Section 2 East field line @ 236000

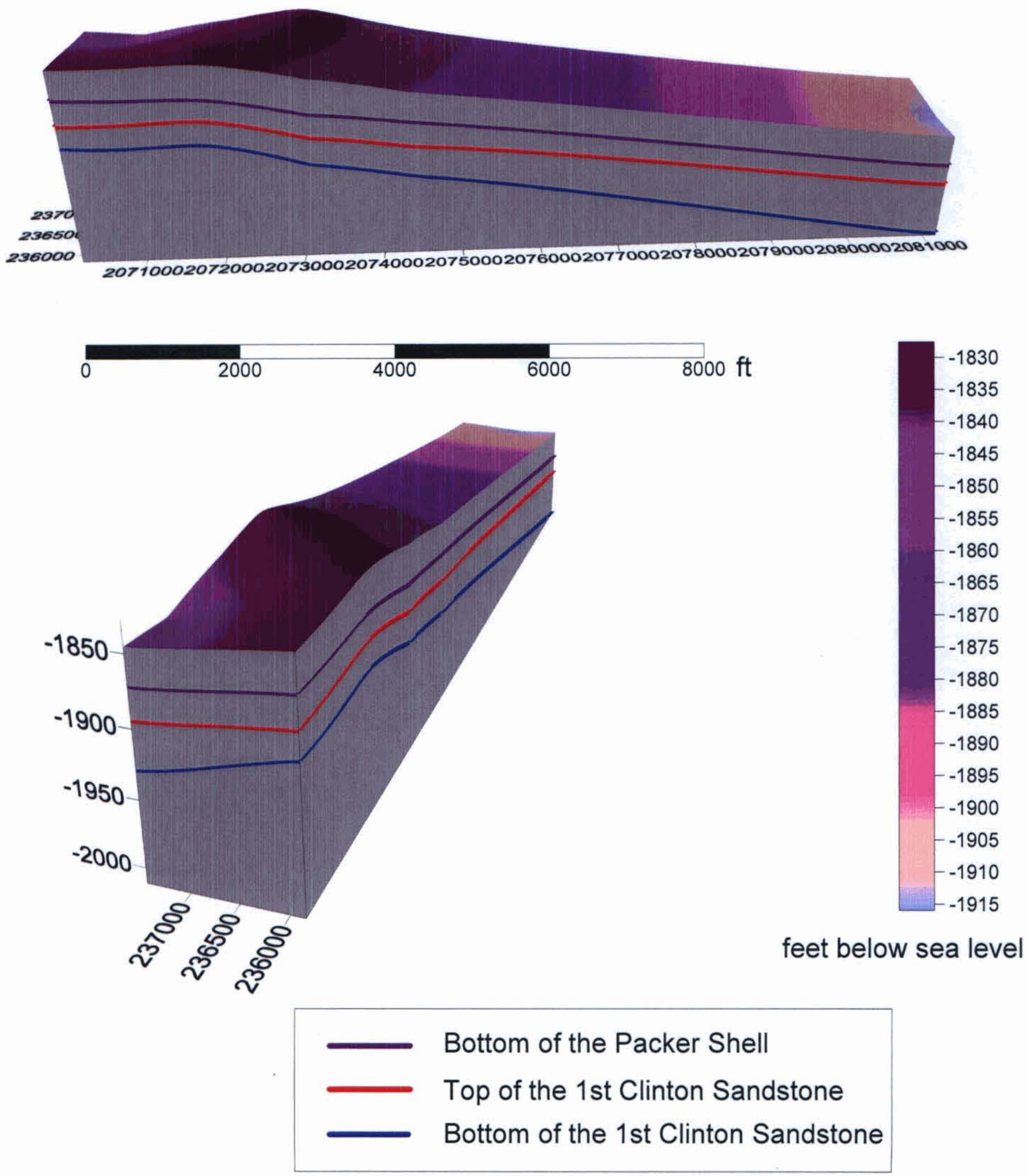
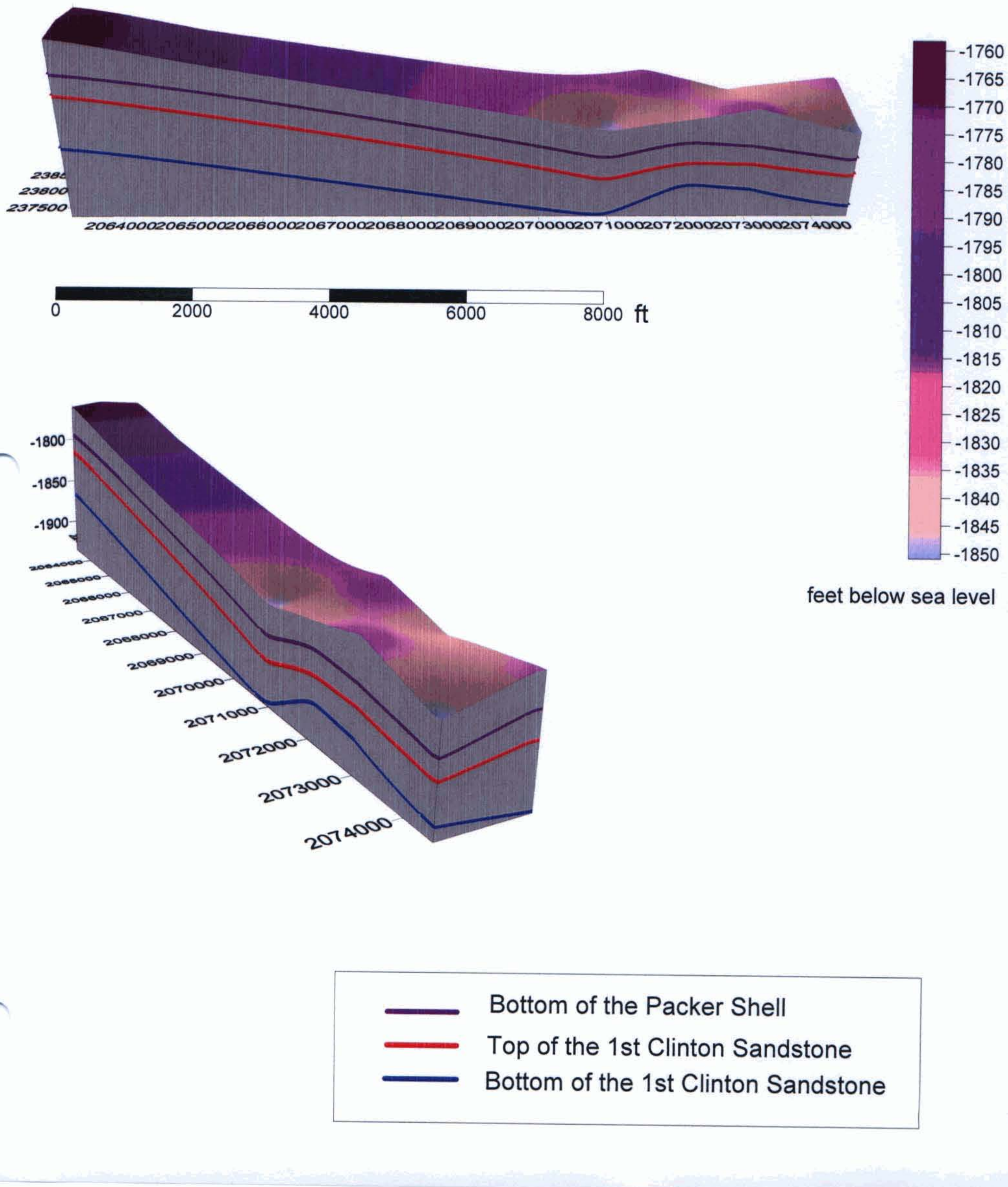


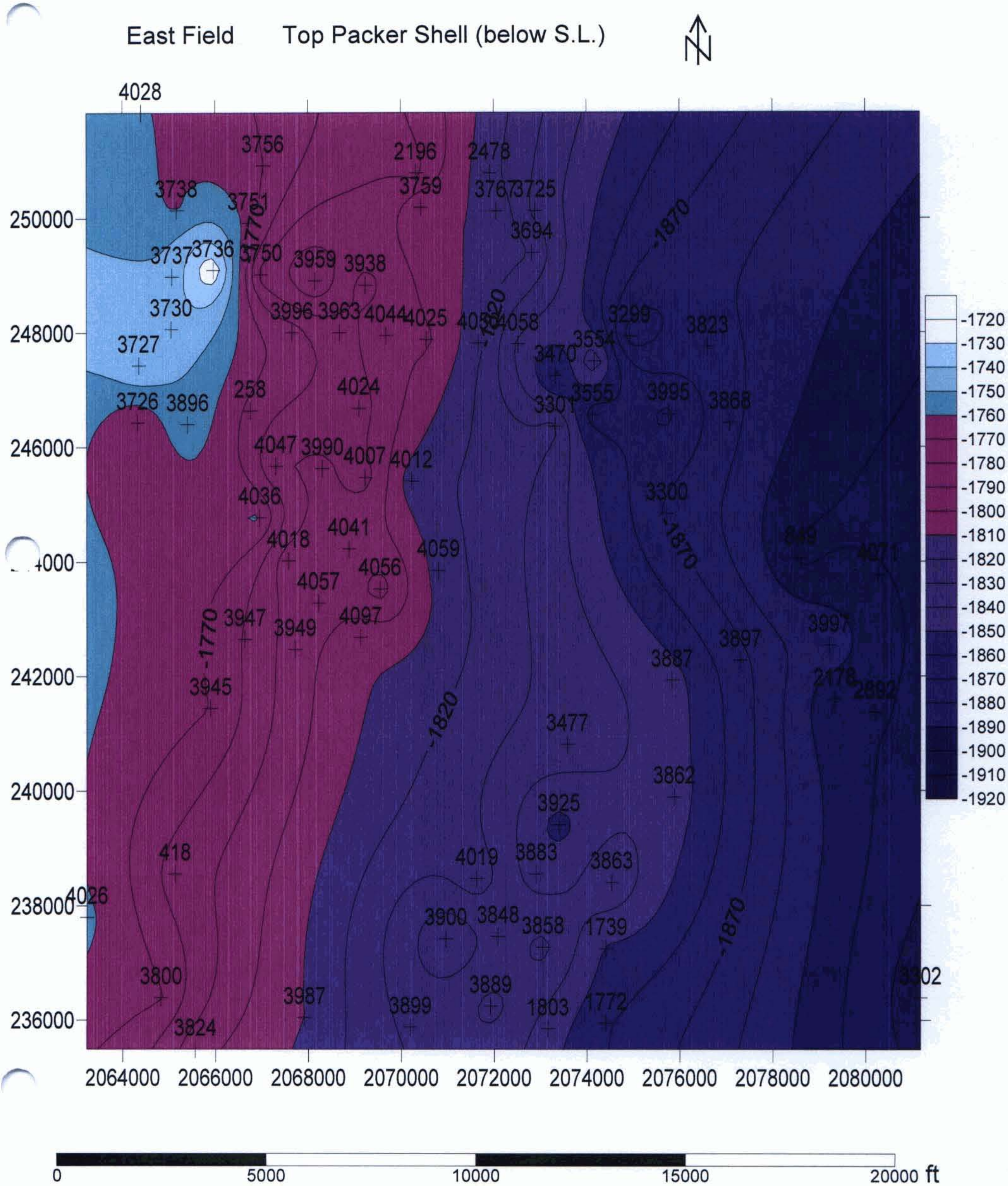
**Figure 36**

Cross section 3  East Field  line at 237500



# Figure 37

East Field Top Packer Shell (below S.L.)



# Figure 38

East Field Bottom Packer Shell ( below S.L.)

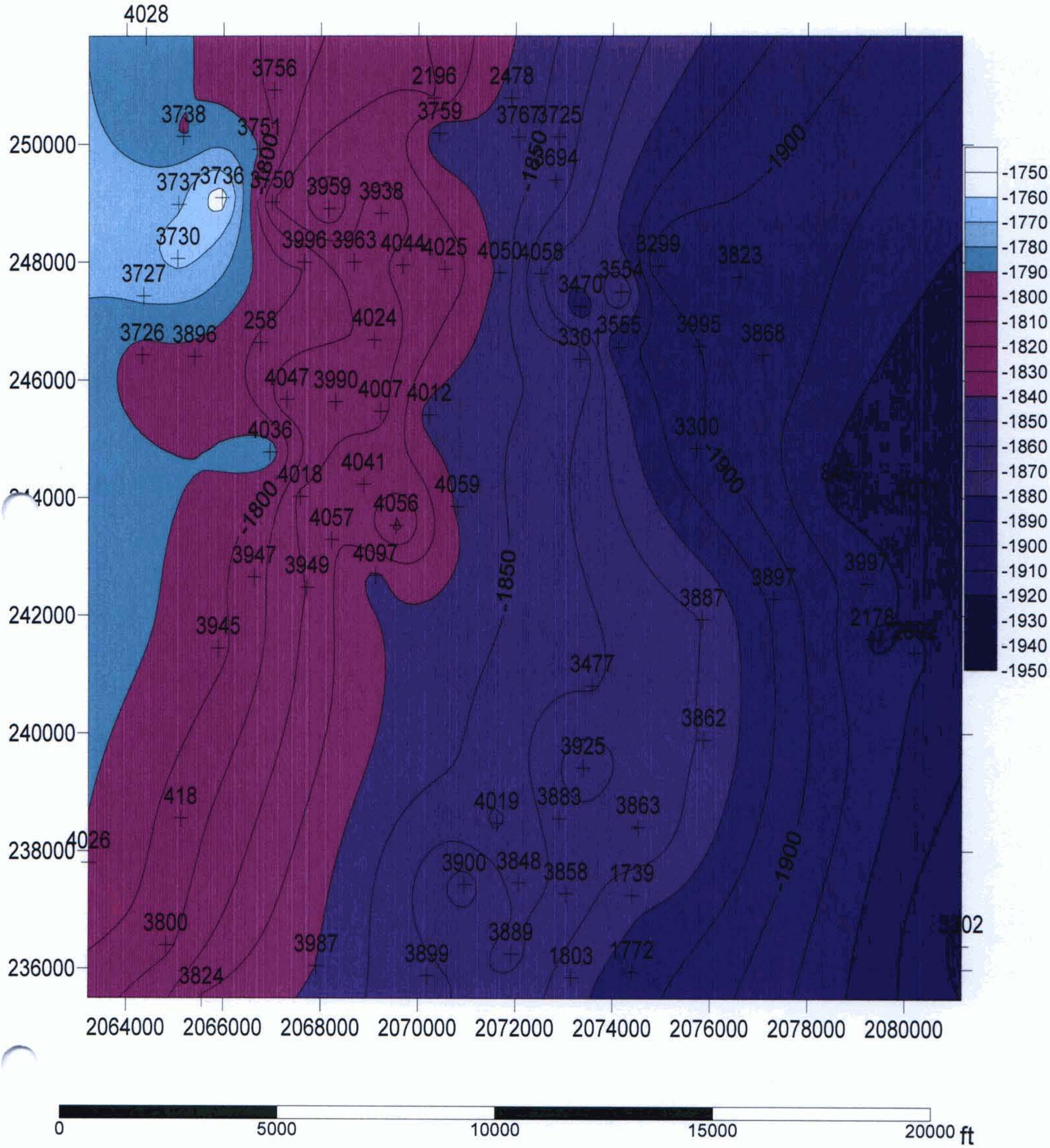
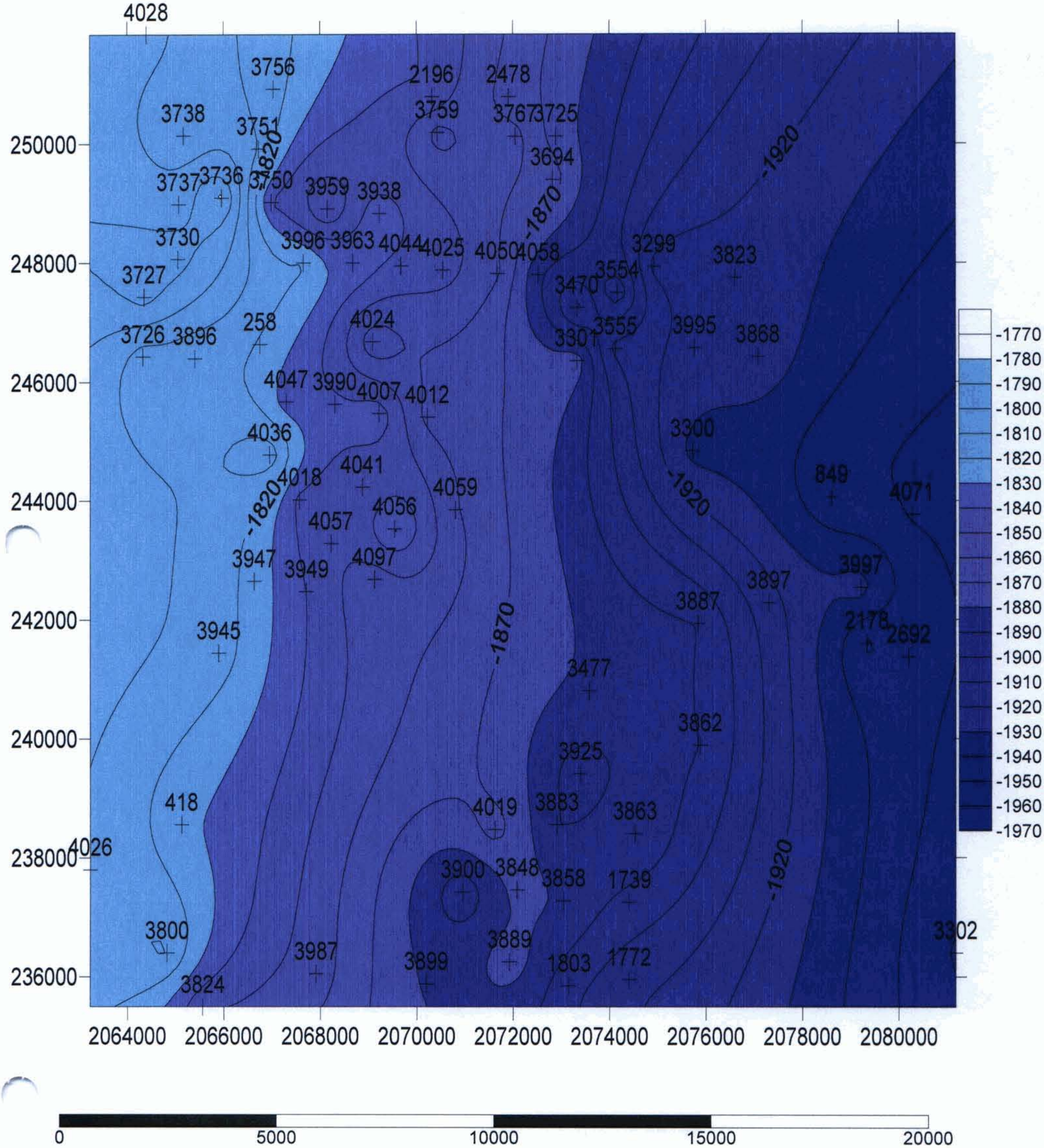


**Figure 39**

East Field Top of 1st Clinton Sandstone (below S.L.)



# Figure 40

East Field Bottom 1st Clinton Sandstone (below S.L.)

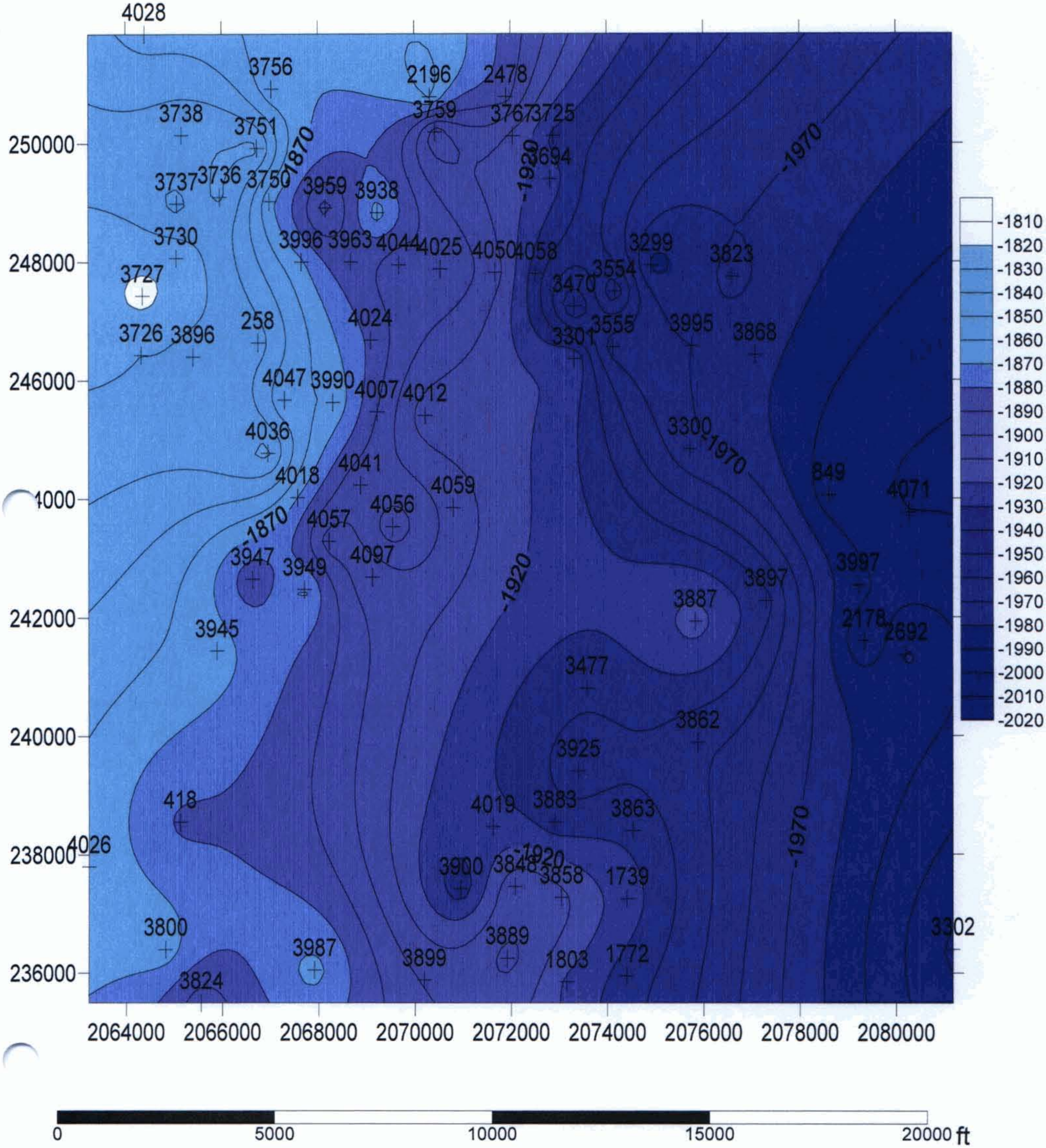


**Figure 41**

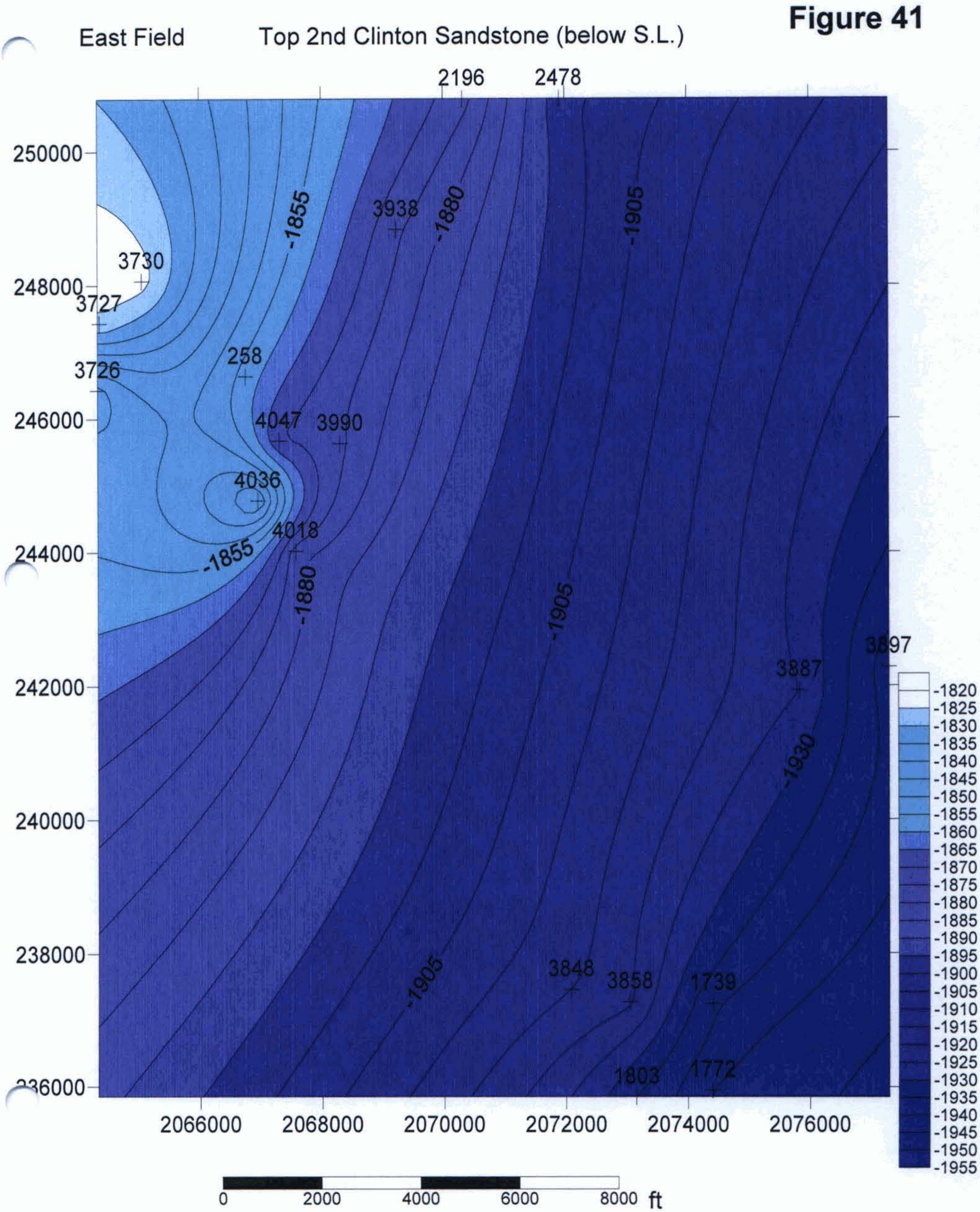

East Field
Top 2nd Clinton Sandstone (below S.L.)
2196
2478
3938
3730
3727
3726
258
4047
3990
4036
4018
3897
3887
3848
3858
1739
1803
1772
-1855
-1880
-1905
-1930
250000
248000
246000
244000
242000
240000
238000
236000
2066000
2068000
2070000
2072000
2074000
2076000
-1820
-1825
-1830
-1835
-1840
-1845
-1850
-1855
-1860
-1865
-1870
-1875
-1880
-1885
-1890
-1895
-1900
-1905
-1910
-1915
-1920
-1925
-1930
-1935
-1940
-1945
-1950
-1955
0
2000
4000
6000
8000
ft

**Figure 42**

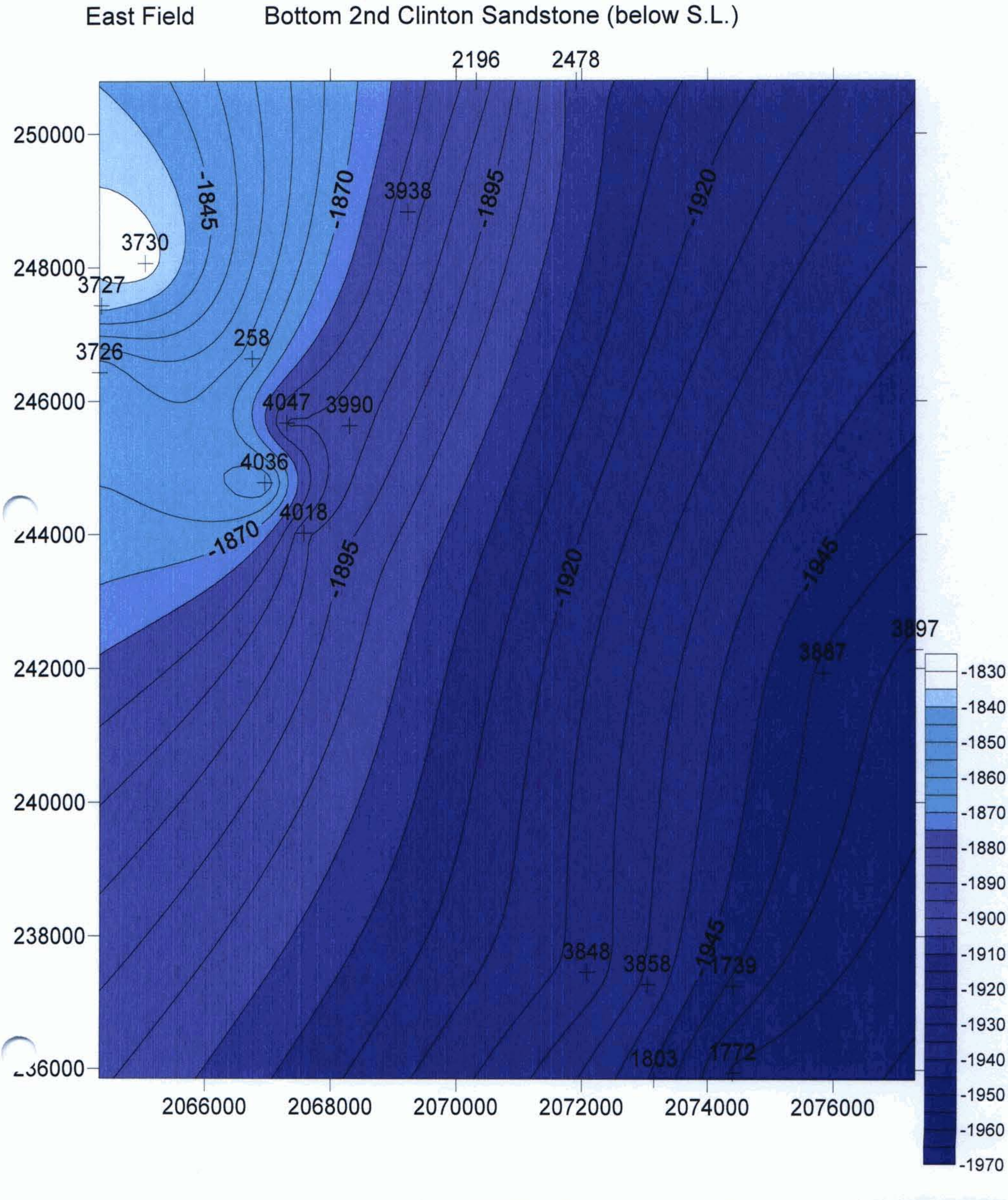

East Field
Bottom 2nd Clinton Sandstone (below S.L.)
2196
2478
250000
248000
246000
244000
242000
240000
238000
236000
2066000
2068000
2070000
2072000
2074000
2076000
-1845
-1870
-1895
-1920
-1945
3938
3730
3727
3726
258
4047
3990
4036
4018
3897
3867
3848
3858
1739
1803
1772
-1830
-1840
-1850
-1860
-1870
-1880
-1890
-1900
-1910
-1920
-1930
-1940
-1950
-1960
-1970

**Figure 43**

East Field Net Packer Shell Thickness